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Wind Energy Potential in New Mexico

J. W. Reed, R. C. Maydew, B. F. Blackwell

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WIND ENERGY POTENTIAL IN NEW MEXICO

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ABSTRACT

The history and state of the art of wind turbines is briefly discussed. Estimates of wind energy available in the USA are noted. Although a preliminary estimate of the wind energy potential for New Mexico shows that it is more than adequate to serve local needs without severe environmental impact, several windier regions appear more attractive for wind turbine fields designed to generate energy for export.

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FOREWORD

The Energy Task Force, State of New Mexico (Governor Bruce King, Chairman), requested that position papers be prepared on various aspects of energy which might impact New Mexico. Professor Harold A. Daw, Associate Director, Arts and Sciences Research Center, New Mexico State University, agreed to chair a group for preparing a position paper on wind energy. This report on the history and status of wind turbines and the meteorological considerations of the wind energy potential in New Mexico was prepared, at the request of Professor Daw, as part of the position paper.

WIND ENERGY POTENTIAL IN NEW MEXICO

Wind Turbines

History

Wind was one of the first natural energy sources to be harnessed by man. Golding[1] indicates that windmills were used in Babylon and in China around 1700 to 2000 BC, in Persia around 644 AD, and in Europe from the 8th Century AD. Early windmills were used for pumping water and grinding grain. According to Golding there were, at one time, some 10,000 windmills operating in Great Britain; in 1750, 8000 in Holland; and, in 1895, 18,000 in Germany. There were some 3000 windmills in Portugal as late as 1965.[2] A decline in the number resulted from development of the steam engine by the Scottish engineer, James Watt, in the 18th Century and widespread usage of this device during the industrial revoluation. Later developments of many devices that utilized electricity and storage batteries, however, prompted some temporary resurgence of windmill activities. Denmark, which lacks fossil fuel and hydroelectric energy sources, was the first to generate electricity from wind. In 1890 the Danes developed a rotor wind generator 75 ft (23 m) in diameter. By 1910, some hundreds of wind turbines[3] with generating capacities of 5 to 25 kilowatts (kW) were in operation in their country.

The contribution of the windmill to the development of the western United States involved an estimated 6.5 million units[4] built in this country between 1880 and 1930. Although most of them were used for pumping water and running sawmills, some were used to generate electricity. In the midwest as recently as 1950 there were about 50,000 small wind generators, the most common brands of which were Wincharger (200 to 1200 W) and Jacobs (1.5 to 3 kW). In Russia in 1954 there were about 29,500 wind power plants,[1] with a total output of about 125,000 kW.

The demise of the wind generator in the past 30 years is the result of the availability of cheap (until 1973) fossil fuel and hydroelectric energy (including the supplying of low-cost electrical power to rural areas by REA and TVA).

State of the Art

In 1961, Ulrich Hutter, professor at Stuttgart's Polytechnic Institute, indicated during a lecture at a United Nations Conference in Rome that[5]

> Several hundred thousand wind pumps in semi-arid desert regions of the western United States, South America, the Mediterranean, Australia, and South Africa had helped make possible or had been a precondition for the existence of life on farms there.

> Denmark had improved the energy supply of its rural counties during both world wars with the aid of wind power plants.
>
> From the mid-1920's to the mid-1950's, thousands of farms in the United States depended on wind machines for electrical power for lighting and the operation of radios.
>
> For about thirty years, experimental wind power plants with an output of between 10 and 1000 kW had proved in many countries that electrical energy could be fed into public networks with full automation.
>
> We therefore need no renewed proof that the utilization of wind energy upon certain premises—premises such as are often found in industrially underdeveloped countries—is technically feasible and economically justified.

The greatest value of wind generator seems to lie in isolated regions, where small- or medium-sized generators can provide an alternative source—in some cases, the only source—of power. The main disadvantage of wind power, its intermittent nature, can be overcome with storage methods or standby plants using fuel. Storage methods include mechanical (storing water at a high elevation or gas at high pressure, releasing it when wind is absent, and recovering the power through turbines); batteries; heat storage in rocks or chemical compounds for later recovery; use of a super-high-speed flywheel; and electrolysis of water, later combining the hydrogen and oxygen in a fuel cell.

The largest windmill ever built was conceived by P. C. Putnam[6] and financed by the S. Morgan Smith Company (now part of Allis-Chalmers). This windmill consisted of a two-bladed, variable-pitch (for rotational speed control) propeller, was 175 ft (53 m) in diameter, and was mounted on a 110-ft (34-m) tower on Grandpa's Knob, near Rutland, Vermont. Each stainless steel blade weighed 8 tons (40 m). A 1.25-MW generator was coupled to the AC power grid of the Central Vermont Public Service Corporation. This unit was operated intermittently for 1100 hours from 1941 to 1945. The mean annual wind velocity was found to be 17 mph (8 m/s), despite predesign estimates of mean wind velocity for 24 mph (11 m/s). The windmill operated in winds of up to 70 mph (31 m/s), and its structure withstood winds of 115 mph (51 m/s). This system demonstrated technical feasibility, even though fatigue-induced failure of a stainless steel blade (of inadequate wartime materials) closed down operation. The cost of generated power was about 50 percent greater than the cheap hydroelectric power then available in Vermont. If actual wind speeds had been as large as those anticipated, delivered power might have been a factor of 3 higher $\left[\text{by } (24/17)^3 \approx 3\right]$. In this case, the project might have been an economic success. This fact emphasizes the importance of proper siting for wind turbines.

A three-blade wind turbine 80 ft (24 m) in diameter was built in 1957 in Denmark[7] on the island of Gedser. It was rated to produce 200 kW in a 33.6-mph (15 m/s) wind, apparently with a 21-percent efficiency factor assumed. The electrical generator was located in a rotatable platform housing atop the 85-ft (26-m) tower. The turbine was coupled through a chain drive to a 200-kW induction generator connected to an AC network. Blade spars, tie rods, etc., were fabricated of mild steel plate; the blades were covered with aluminum sheet; and the tower was fabricated of reinforced concrete. This system cost $41,000, or $205 per rated kW. It was dismantled in 1968 after the Danes started importing more cheap hydroelectric power from Sweden's surplus.

The Brace Research Institute at McGill University, Canada, recently constructed a windmill 32 ft (10 m) in diameter for the Barbados government.[8] It is used directly to pump water for irrigation. The propeller consists of three blades manufactured of fiberglass-reinforced epoxy resin.

W. L. Hughes and associates at Oklahoma State University[9] have been studying, under National Science Foundation (NSF) sponsorship, the feasibility of 1- to 50-kW wind units for use as power sources in underdeveloped countries. Their studies include consideration of energy storage by producing hydrogen (and oxygen) through electrolysis of water at high pressure of about 3000 psi, or 21 megapascals (MPa).

In recent years, several other proposals for utilizing windmills have been published. E. W. Hewson and associates of Oregon State University, studying the feasibility of wind power collection for Oregon utility destricts, have estimated that there are 150 suitable wind-generating sites along a 100-mile stretch of the Oregon coast.[10] W. E. Heronemus, of the University of Massachusetts, has proposed[11] building 15,000 850-ft-high (260-m) towers (with twenty 50-ft-diameter (15-m) propellers per tower) on the Great Plains to provide 189×10^6 kW of electrical power. This is apparently based on an assumption of 60-mph (27-m/s) steady wind with 30-percent extraction efficiency, a questionable condition. Heronemus has also proposed[12] building an offshore system, consisting of 83 units, on the Atlantic Ocean. Each unit would comprise 165 340-ft-high (104-m) towers, with three 2-MW propeller/generators per tower. The system would provide 82×10^6 kW of electrical power. Many environmental, economic, and political (as well as engineering) problems would have to be worked out before these gigantic schemes could be seriously considered.

Since 1971 the National Research Council (NRC)[13] of Ottawa, Canada, has developed a vertical-axis wind turbine. It consists of two or three slender blades (of airfoil cross section) attached at the top and bottom of a vertical shaft. The blades bow outward, giving the turbine an eggbeater appearance. Although this vertical-axis turbine was invented in 1925 by G. J. M. Darrieus of Paris, France, his idea lay dormant until reinvented by the NRC team in 1971-72.

Obvious advantages of a vertical-axis turbine include the following: (1) Wind can be accepted from any direction, (2) the generator can be mounted at ground level, (3) blades can be fabricated easily, and (4) tower structure is simple. These advantages should result in lower fabrication costs; NRC[13] estimates the cost to be about one-sixth that of a conventional horizontal-axis turbine. NRC has fabricated and tested vertical-axis systems 12 and 14 ft in diameter (3.7 and 4.3 m).

Sandia Laboratories[14] started a wind-energy R&D program in the fall of 1973. The prime initial objectives were to demonstrate the feasibility of small (1 to 10 kW) self-contained vertical-axis turbine units[15] for use in remote areas and the technical feasibility and cost effectiveness of large (100 to 1000 kW) systems for commercial power production, i.e., to integrate with existing utility grids. Sandia Laboratories currently has a 15-ft-diameter (4.6 m) vertical-axis test bed unit, similar to the model shown in Figure 1, in operation on the roof of the fourth floor of its administration building. The Langley Research Center[16] of the National Aeronautics and Space Administration (NASA) is also doing studies of vertical-axis wind turbines.

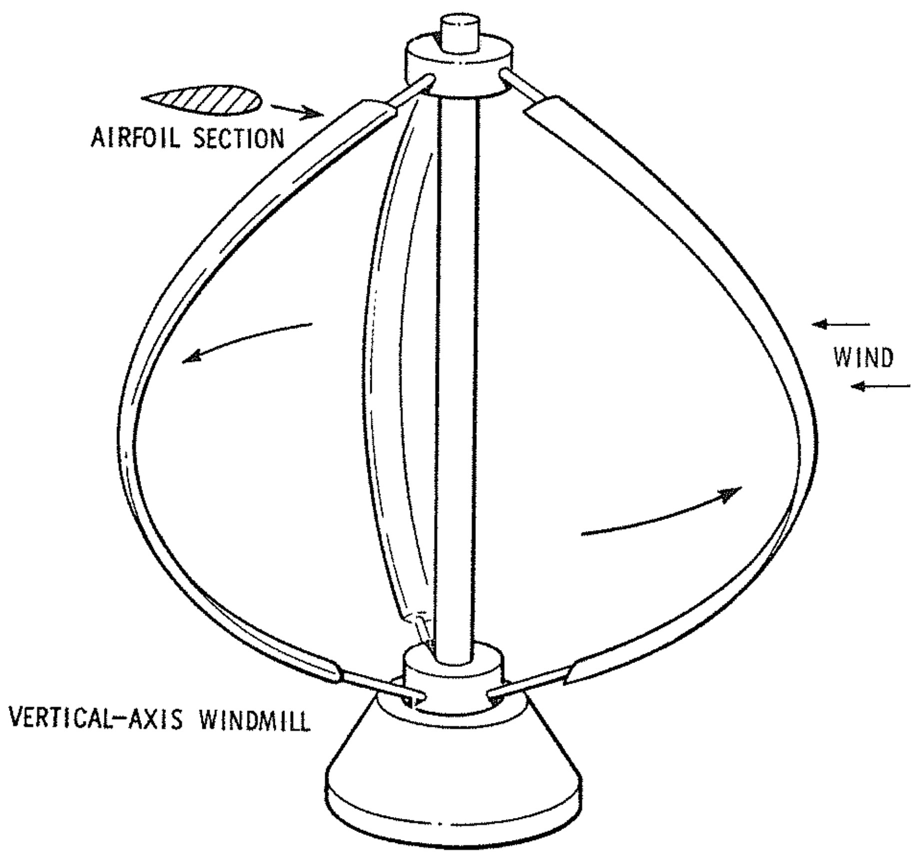

Figure 1. Vertical-Axis Wind Turbine

In March 1974 NSF and NASA announced an agreement for the design, building, and testing of a 100-kW wind turbine generator (horizontal-axis) to be erected and tested at the NASA-Lewis Plum Brook test area, near Sandusky, Ohio. Their project objective is to determine the performance, operating, and economic characteristics of such systems for the future generation of commercial electric power and to identify technical problems and areas where research and advanced concepts could increase performance and decrease costs. Winds at Plum Brook average 10 mph (4.5 m/s), and the aerogenerator reaches its 100-kW rated output at 18-mph (8-m/s) wind speeds. The system is expected to generate 180,000 kWh per year in the form of 460-volt, three-phase, 60-Hz AC output. NSF support for this two-year project is $865,000; NASA will supply funds for personnel salaries and services. Funding and approval for NSF/NASA to start designing a follow-on 1-MW horizontal-axis wind turbine is expected soon.

Recommended funding[17] for USA wind-energy R&D for the period FY'75-FY'79 varies from $26.9 million (minimally viable program) to $106.2 million (accelerated program).

Wind Energy Potential

Wind Energy Available

Increasing fossil-fuel costs have forced this nation to consider development of alternative energy sources. The largest naturally occurring energy source is the sun. It has been estimated that approximately 2 percent of the solar energy deposited on earth is converted to wind energy. The World Meteorological Organization[18] has estimated that 20×10^9 kW of wind power is available at selected sites throughout the world. Note that the total electricity-generating capacity in the USA in 1972 was 0.46×10^9 kW (1×10^9 kW for the world), and usage was 1.6×10^{12} kWh.

The potential of the wind as a plentiful, nonpolluting energy source has come into focus in two recent national energy workshop meetings[19,20] sponsored jointly by NSF and NASA. These groups have estimated (see Table I) that 1.54×10^{12} kWh electricity could be produced annually by the year 2000 from practical wind power sites in Alaska, the Great Plains, and the Great Lakes, as well as offshore New England, Eastern Seaboard, and Texas Gulf coasts.

TABLE I

Estimated Electrical Energy Production From Wind Power (from Ref. 19)

Site	Annual Power Production
Offshore, New England	318×10^9 kWh
Offshore, Eastern Seaboard	283×10^9 kWh
Offshore, Texas Gulf Coast	190×10^9 kWh
Great Lakes	133×10^9 kWh
Great Plains	210×10^9 kWh
Aleutian Chain	402×10^9 kWh
Total	1536×10^9 kWh

Wind Power Estimates

Wind power, P, is calculated from the kinetic energy, KE, per unit of time, t,

$$P = \frac{KE}{t} = \frac{mV^2}{2t} = \frac{1}{2}\dot{m}V^2 = \frac{1}{2}\rho A V^3 \qquad (1)$$

where m is mass and $\dot{m}$ its flow rate, V is wind speed, ρ is air density, and A is cross-section area perpendicular to the flow. For a square meter perpendicular to the wind, with various coefficients appropriate for available input wind data and with standard sea level air density, the power per unit area is

$A_s\{15\text{ ft}\} = 14.68\text{ m}^2$

$$\frac{P}{A} = 0.6125V^3 \text{ Wm}^{-2}, \text{ V in m/s}$$

$$= 0.05472V^3 \text{ Wm}^{-2}, \text{ V in mph}$$

$$= 0.08355V^3 \text{ Wm}^{-2}, \text{ V in knots.} \qquad (2)$$

This cubic response to wind speed requires use of a climatological distribution of speeds, rather than an average speed, for calculating wind power. If the wind were a steady 15 mph (6.7 m/s), 185 Wm^{-2} would be available. If it blew 10 mph (4.5 m/s) half the time and 20 mph (8.9 m/s) half the time, again averaging 15 mph (6.7 m/s), it would yield 245 Wm^{-2}. Also, this cubic response makes the particular anemometer exposure very important because wind speed is affected by the surrounding environment of buildings, hills, or trees, as well as height above the ground friction level.[21] For example, where a 5-m/s wind speed could be doubled to 10 m/s at some greater height, the power would be increased 8 times. Available data are, unfortunately, not very consistent in regard to exposure; however, "standard" anemometer exposure has been defined as 10 m (33 ft) above level ground and away from any obstructions. Hence, no great confidence can be placed in the applicability of power figures calculated from published wind records. It must suffice for the moment, however, to use what data are available, mostly from airport weather observing stations. Information from especially instrumented installations will be used in a later section in an attempt to define the effects of heights and obstructions.

In order to determine what geographical areas of the nation are best suited for the exploitation of wind power, wind speed distributions were obtained from the Environmental Science Service Administration (ESSA).[22] That agency has been redesignated National Oceanic and Atmospheric Adminstration (NOAA). Table II shows the percentage of time that the wind blows in the indicated ranges of wind speed. Unless the wind speed is greater than 10 mph (4.5 m/s) for an appreciable percentage of the time, wind power extraction will probably not be practical. The speed at which wind power generation becomes economically feasible obviously depends upon the specific application. For example, if fuel must be brought in by air transport, as is the case for remote Alaskan communities, then wind energy will be competitive with conventional power sources at a much lower wind speed than if the wind turbine site were located adjacent to an existing fossil-fuel steam-generating station in the coterminous states.

TABLE II

Annual Percentage Frequency of Wind by Speed Groups*
(from ESSA[22])

STATE AND STATION	0 - 3 m.p.h.	4 - 7 m.p.h.	8 - 12 m.p.h.	13 - 18 m.p.h.	19 - 24 m.p.h.	25 - 31 m.p.h.	32 - 38 m.p.h.	39 - 48 m.p.h.	47 m.p.h. and over	Mean speed m.p.h.
ALA. Birmingham	27	22	30	17	3	1	*	*	*	7.9
Mobile	7	28	38	20	6	1	*	*	*	10.0
Montgomery	31	29	27	12	2	*	*			6.9
ALASKA, Anchorage	28	35	25	11	2	*	*	*		6.8
Cold Bay	4	9	18	27	21	14	5	2	*	17.4
Fairbanks	40	35	19	5	1	*	*	*		5.2
King Salmon	11	20	30	24	10	4	1	*	*	11.4
ARIZ. Phoenix	38	36	20	5	1	*	*	*		5.4
Tucson	18	35	30	14	3	1	*	*		8.1
ARK. Little Rock	12	30	39	16	2	*	*	*		8.7
CALIF. Bakersfield	25	30	24	10	1	*	*			5.8
Burbank	32	26	18	4	1	*	*	*		4.5
Fresno	30	41	22	7	1	*	*			6.1
Los Angeles	28	33	27	11	1	*	*			6.8
Oakland	26	28	28	16	2	1	*	*	*	7.5
Sacramento	15	28	31	18	5	1	*	*	*	9.3
San Diego	28	38	28	6	*	*	*			6.3
San Francisco	16	21	26	22	11	3	*	*	*	10.6
COLO. Colorado Springs	9	27	38	19	6	2	*	*	*	10.0
Denver	11	27	34	22	5	2	*	*	*	10.0
CONN. Hartford	13	26	32	24	6	1	*	*	*	9.8
D.C. Washington	11	26	35	22	5	1	*	*	*	9.7
DEL. Wilmington	15	31	30	19	4	1	*	*	*	8.8
FLA. Jacksonville	10	33	35	18	3	*	*	*		8.9
Miami	14	30	34	20	2	*	*	*	*	8.8
Orlando	18	28	32	17	4	*	*	*		8.6
Tallahassee	33	36	23	7	*	*				6.1
Tampa	9	31	40	16	2	*	*	*	*	8.8
West Palm Beach	9	22	36	27	6	1	*	*		10.5
GA. Atlanta	13	24	36	21	6	1	*	*		9.7
Augusta	36	29	25	9	1	*	*			6.3
Macon	10	26	46	16	2	*	*	*	*	8.9
Savannah	12	34	37	14	3	*	*	*	*	8.4
HAWAII, Hilo	7	34	43	15	2	*	*			8.7
Honolulu	9	17	27	32	12	2	*	*	*	12.1
IDAHO. Boise	15	30	32	18	4	1	*	*		8.9
ILL. Chicago (O'Hare)	8	22	33	27	8	2	*	*	*	11.2
Chicago (Midway)	7	26	35	25	5	1	*	*	*	10.2
Moline	14	23	32	24	7	2	*	*	*	10.0
Springfield	7	22	28	27	12	3	1	*	*	12.0
IND. Evansville	19	23	32	21	5	1	*	*		9.1
Fort Wayne	9	23	33	25	8	2	*	*	*	10.9
Indianapolis	9	22	34	26	7	2	*	*	*	10.8
South Bend	7	21	35	30	7	1	*	*		10.9
IOWA. Des Moines	3	17	38	29	10	3	1	*	*	12.1
Sioux City	10	20	31	25	10	4	1	*	*	11.7

STATE AND STATION	0 - 3 m.p.h.	4 - 7 m.p.h.	8 - 12 m.p.h.	13 - 18 m.p.h.	19 - 24 m.p.h.	25 - 31 m.p.h.	32 - 38 m.p.h.	39 - 46 m.p.h.	47 m.p.h. and over	Mean speed m.p.h.
KANS. Topeka	11	19	30	27	10	2	*	*	*	11.2
Wichita	4	12	30	31	16	5	1	*	*	13.7
KY. Lexington	8	25	39	22	6	1	*	*		10.1
Louisville	17	28	31	20	3	1	*	*		8.8
LA. Baton Rouge	17	29	34	17	3	*	*	*		8.3
Lake Charles	19	31	29	17	4	1	*	*	*	8.5
New Orleans	16	27	32	19	5	1	*	*	*	9.0
Shreveport	12	26	37	21	4	1	*	*	*	9.5
MAINE, Portland	10	30	33	22	4	1	*	*	*	9.6
MD. Baltimore	7	24	39	22	6	2	*	*	*	10.4
MASS. Boston	3	12	33	35	12	4	1	*	*	13.3
MICH. Detroit (City AP)	8	23	37	26	5	1	*	*	*	10.3
Flint	16	26	32	22	3	1	*	*	*	9.0
Grand Rapids	14	23	32	25	5	1	*	*	*	9.8
MINN. Duluth	6	15	33	31	11	4	1	*	*	12.6
Minneapolis	8	21	34	28	9	2	*	*	*	11.2
MISS. Jackson	33	25	26	14	2	*	*	*		7.1
MO. Kansas City	9	29	35	23	5	1	*			9.8
St. Louis	10	29	36	21	3	1	*	*	*	9.3
Springfield	4	13	34	32	13	3	1	*	*	12.9
MONT. Great Falls	7	19	24	24	15	9	3	1	*	13.9
NEBR. Omaha	12	17	29	28	11	3	*	*		11.6
NEV. Las Vegas	18	26	25	20	8	3	1	*	*	9.7
Reno	52	20	13	10	4	1	*	*	*	5.9
N. J. Newark	11	25	34	24	5	1	*	*	*	9.8
N. MEX. Albuquerque	17	36	26	13	5	2	*	*	*	8.6
N. Y. Albany	23	24	27	21	4	1	*	*		8.6
Binghamton	11	23	35	25	5	1	*	*	*	10.0
Buffalo	5	17	34	27	13	3	1	*	*	12.4
New York (Kennedy)	6	17	35	28	10	3	*	*	*	12.0
New York (La Guardia)	6	15	30	31	12	4	1	*	*	12.9
Rochester	8	22	34	25	9	2	1	*	*	11.2
Syracuse	14	27	30	23	5	1	*	*	*	9.7
N. C. Charlotte	20	32	31	14	2	*	*	*		7.9
Greensboro	20	32	31	14	2	*	*	*	*	8.0
Raleigh	18	33	34	14	2	*	*	*	*	7.7
Winston-Salem	19	22	33	21	4	1	*	*		9.0
N. DAK. Bismarck	14	20	27	24	12	3	1	*	*	11.2
Fargo	4	13	28	31	15	7	2	*	*	14.4
OHIO, Akron-Canton	7	25	35	26	5	1	*	*	*	10.4
Cincinnati	11	27	36	22	4	1	*	*	*	9.6
Cleveland	7	18	35	29	9	2	*	*	*	11.6
Columbus	26	23	29	18	4	1	*	*	*	8.2
Dayton	8	25	36	23	6	2	*	*	*	10.3
Youngstown	7	20	36	24	6	1	*	*	*	10.3
OKLA. Oklahoma City	2	11	34	34	13	6	1	*	*	14.0

STATE AND STATION	0 - 3 m.p.h.	4 - 7 m.p.h.	8 - 12 m.p.h.	13 - 18 m.p.h.	19 - 24 m.p.h.	25 - 31 m.p.h.	32 - 38 m.p.h.	39 - 46 m.p.h.	47 m.p.h. and over	Mean speed m.p.h.
OKLA. (Cont.) Tulsa	9	24	34	26	7	1	*	*	*	10.6
OREG. Medford	47	31	14	6	2	*	*	*	*	4.6
Portland	28	27	25	16	4	1	*	*	*	7.7
Salem	25	32	28	13	2	*	*			7.1
PA. Harrisburg	28	31	25	13	3	1	*	*		7.3
Philadelphia	11	27	35	21	5	1	*	*	*	9.6
Pittsburgh	12	26	34	22	4	1	*	*		9.4
Scranton	11	33	35	18	2	*	*	*		8.8
R. I. Providence	11	20	32	28	7	2	*	*	*	10.7
S. C. Charleston	12	28	35	19	4	1	*	*		9.2
Columbia	25	35	26	12	2	*	*			7.0
S. DAK. Huron	10	18	29	29	10	3	1	*	*	11.9
Rapid City	15	22	28	21	10	4	1	*	*	11.0
TENN. Chattanooga	39	25	24	11	1	*	*			6.1
Knoxville	29	29	25	12	4	1	*	*	*	7.5
Memphis	14	26	34	20	5	1	*	*		9.4
Nashville	27	31	25	14	2	*	*	*	*	7.2
TEX. Amarillo	5	15	32	32	12	4	1	*	*	12.9
Austin	13	25	34	23	5	1	*	*		9.7
Brownsville	10	17	25	30	14	3	*	*	*	12.3
Corpus Christi	11	16	26	33	12	2	*	*		11.9
Dallas	9	21	32	28	9	1	*	*		11.0
El Paso	10	22	32	22	9	4	1	*	*	11.3
Ft. Worth	4	14	34	34	10	3	*	*	*	12.5
Galveston	4	13	39	33	10	2	1	*	*	12.5
Houston	6	18	36	28	10	2	*	*	*	11.8
Laredo	6	15	32	34	12	1	*	*		12.3
Lubbock	4	11	33	34	13	5	1	*	*	13.6
Midland	9	22	38	26	4	1	*	*		10.1
San Antonio	18	23	32	22	4	1	*	*		9.3
Waco	3	14	36	35	10	2	*	*		12.5
Wichita Falls	5	22	41	27	5	1	*	*	*	10.5
UTAH, Salt Lake City	12	33	36	14	4	1	*	*	*	8.7
VT. Burlington	24	24	28	22	2	*	*			8.3
VA. Norfolk	14	23	30	25	6	1	*	*	*	10.2
Richmond	14	37	36	11	1	*	*	*		7.8
Roanoke	31	22	23	17	5	2	*	*		8.3
WASH. Seattle-Tacoma AP	13	16	35	26	8	2	*	*	*	10.7
Spokane	17	38	27	14	3	1	*	*		8.1
W. VA. Charleston	29	37	25	8	1	*	*			6.2
WIS. Green Bay	8	22	32	26	10	2	*	*	*	11.2
Madison	15	22	30	23	7	2	*	*	*	10.1
Milwaukee	8	17	31	30	11	3	1	*	*	12.1
WYO. Casper	8	16	27	27	13	7	2	*	*	13.3
PACIFIC, Wake Island	1	6	27	48	17	2	*	*		14.6
P. R. San Juan	15	28	27	25	4	*	*	*	*	9.1

Source: Climatography of the United States Series 82; Decennial Census of the United States Climate -- Summary of Hourly Observations, 1951-60 (Table B).

*1 mph = 0.447 metre per second (m/s).

The power-producing potential of various geographical areas of the United States was calculated by Eq. (2), using the speed distributions in Table II. Annual averages of power available are presented in Figure 2. Solid-line contours represent locations where the average wind power remains constant. Note that steady wind velocities of 10, 15, and 20 mph (4.5, 6.7, and 8.9 m/s) at sea level correspond to wind power values of 55, 185, and 438 W/m^2, respectively. These areal energy densities are comparable to those from direct solar radiation. About 40 percent of this energy can probably be extracted with a wind turbine. Most promising wind power sites lie on the northeast and northwest coast lines, the western Great Plains, and the Great Lakes areas. These data should be taken as being only roughly representative of how the average wind power varies over large geographical areas. For smaller geographical areas, there will be detailed exceptions to this general pattern. In particular, adjacent regions in mountainous areas can experience widely differing average power because of variations in terrain.

Data from Figure 2 were rather sparse and there were many questions about the representativeness of many of the numbers. Most were obtained at well-exposed airport locations, but at uncertain heights. Some anemometers were on hangars, others on control towers, and possibly a few were placed at the "standard" 10-m height above open ground. Consequently, this pattern is tentative, pending receipt of better data and from more stations. To this end, Sandia Laboratories is negotiating with the National Climatic Center (NCC) of NOAA at Asheville, North Carolina, to process records from a selection of nearly six-hundred weather stations with over five years of record. This will provide a redundancy of data so that appropriate objective smoothing procedures can be applied to generate a more confident map pattern of available wind power.

Evaluation of New Mexico's Potential

New Mexico Windstorms

New Mexico has been judged by many to be a particularly windy state because of some truly impressive, though short-lived, wind phenomena. Several times during the spring, when late-season storms blanket the area with a week-end of 30- to 50-mph (13- to 22-m/s) gales, and gusts of 70 or 80 mph (26 or 31 m/s), any transient would swear never to return. Unfortunately, these storms hit in the very driest season. They are thus able to pick up vast quantities of dust and sand, cut visibility to near zero, infiltrate even the tightest homes with a spread of fine silt, and sandblast the windshields of unhappy motorists caught heading in the wrong direction.

In midwinter, when cold polar air masses push south across the Great Plains, they may pile up against the east slope of the mountains of central New Mexico. If a cold air outbreak is deep enough, it may spill westward over this mountain barrier and crash into the central Rio Grande Valley to give the strongest winds ever officially recorded around Albuquerque, 95 mph (42 m/s), and, unofficially, even 105 mph (48 m/s) on rare occasions.

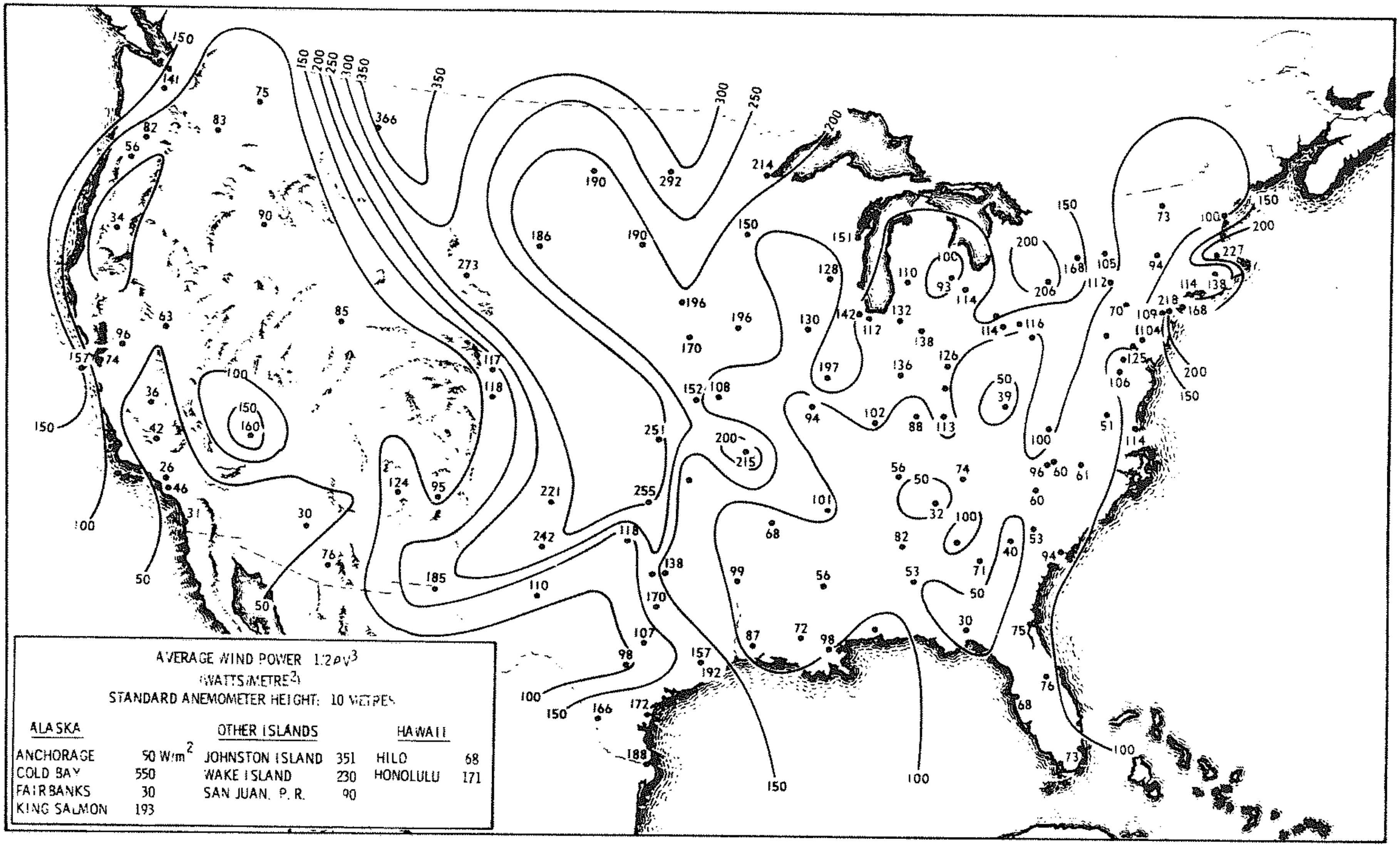

Figure 2. Annual Average Available Wind Power

In summer, clear dry skies allow strong ground heating by the sun that, in turn, creates rising bubbles of convection that frequently set off dust devils. These tiny cyclones may have wind speeds of 60 mph (27 m/s) and are capable of damaging homes and trees with direct hits. Finally, when the monsoon rainy season comes in July and August, there is enough moisture in the air, brought in across Texas from the Gulf of Mexico, to give tall cumulonimbus thunderstorms as a result of solar heating and convective bubbling. As rain falls from these clouds, with bases often more than 5000 ft (1500 m) above ground level, it may take 5 minutes or more to reach the surface. Often it never does reach ground, but appears as virga (the rain streamers which dangle so enticingly from the threatening black storm clouds), because the raindrops evaporate. As they evaporate, they cool the column of air in which they are falling, giving it higher density than the surrounding air and generating a strong downdraft. As this cold gust falls, it builds up speed so that, when it finally strikes the ground, it may hit with 60- to 75-mph (27- to 34-m/s) gust speeds. Again, wind damages may result. If the ground is dry, this blast will pick up sand and dust and appear as an advancing dirty brown wall of cloud.

Hurricanes never reach New Mexico with any significant wind; however, on rare occasions they do bring in heavy rains. Also, tornadoes are relatively rare in New Mexico, with an annual occurrence and damage probability per unit area of only 10 percent of that in Oklahoma, and a per-person fatality hazard of only 4 percent of that in Arkansas.[23]

During the remainder of the year, winds in New Mexico are relatively light. The mountains block many storm circulations. Clear skies allow strong nighttime cooling of the ground surface and the adjacent layer of air. This stabilized air usually prevents the general upper air circulation from penetrating to the ground except during the hours from midmorning until about sunset. In consequence, the average annual wind speed in New Mexico is only 50 to 75 percent of that in neighboring states to the east.

It does appear, nevertheless, that certain features of New Mexico and its winds could be profitably exploited to provide energy from wind power. To date, appropriate wind data collections[22,24-28] have been found for only a few scattered locations in New Mexico and its immediate surroundings, as shown in Table III. Data from several additional stations are expected from the national wind power evaluation currently being processed by NCC. Annual average wind power, as calculated from Eq.(2), is shown in Figure 3 with contour lines of equal power expectation.

To estimate power where only mean or average speed values were available,[26,28] a correlation graph (see Fig. 4) may be used. Wind power per square metre exposed, from actual distributions,[22*] have been plotted versus power calculated for the average wind speed, $P(\bar{V})$, for United States stations reported by ESSA.[21] Some of the extreme points are identified, along with points from New Mexico or nearby. This shows that assumed relationships, based on a particular station, may fail by a factor of up to 2.5 in predicting power from the mean wind at some other station.

*See Table II.

TABLE III

New Mexico Wind Power Data

Station	Average Wind Speed (mph)	(m/s)	Average Wind Power (STP)* Wm^{-2}	Reference
Acomita	10.9	4.9	123	23
Albuquerque	8.6	3.8	95	22
Clayton	14.6	6.5	347	25
El Morro	9.2	4.1	100	23
Rodeo	10.7	4.8	150	23
Roswell	9.6	4.3	124	25
Sandia Crest†	15.3	6.8	518	27
Tucumcari	11.7	5.2	181	23
White Sands	6.9	3.1	56	26
Zuni	9.8	4.4	124	24

*Standard temperature (15°C, 288 K) and pressure (101.3 kPa) at mean sea level altitude.

†Gusts up to 135 mph have been recorded.

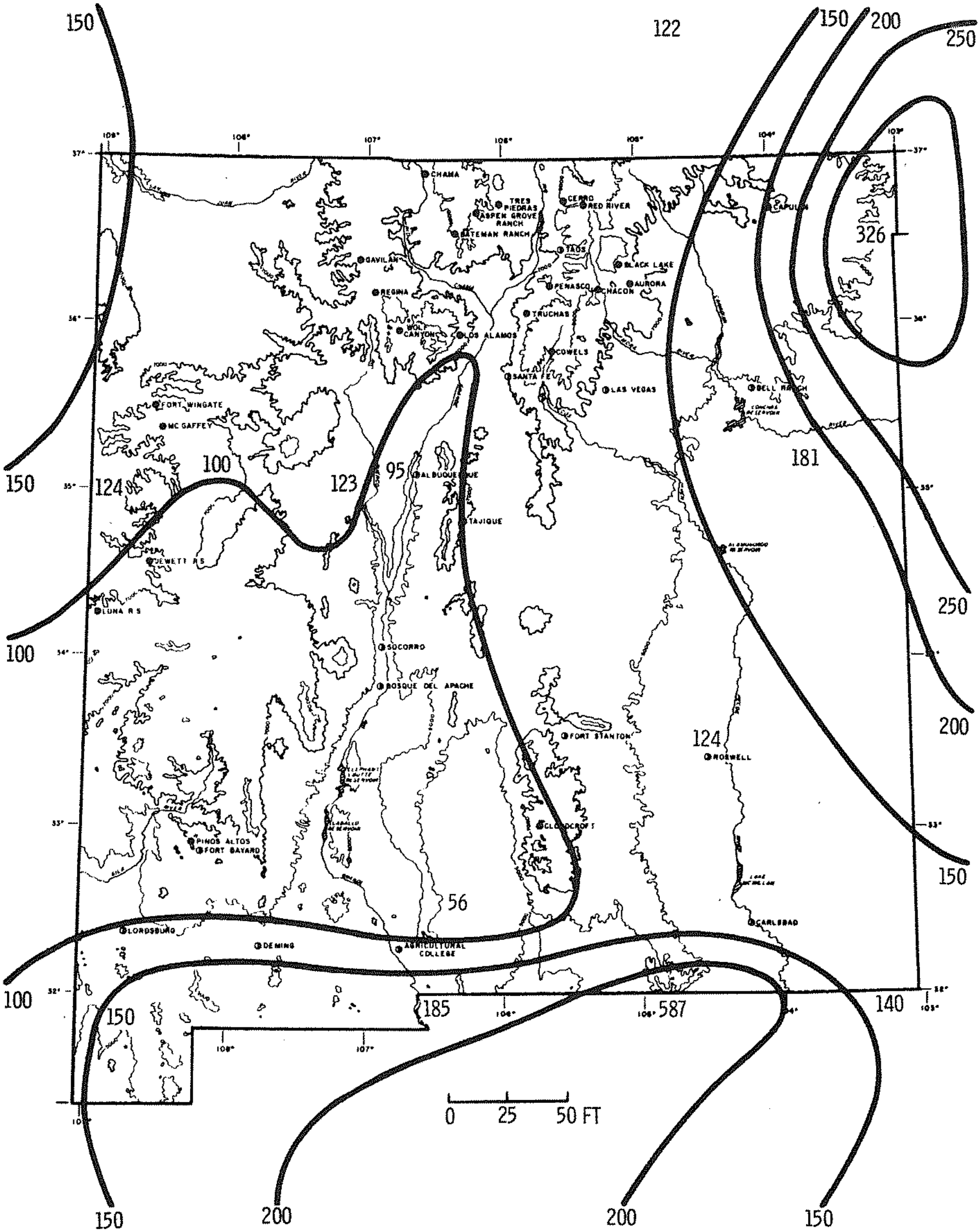

Figure 3. Total Power in the Surface Wind, Annual Averages, in Wm^{-2}

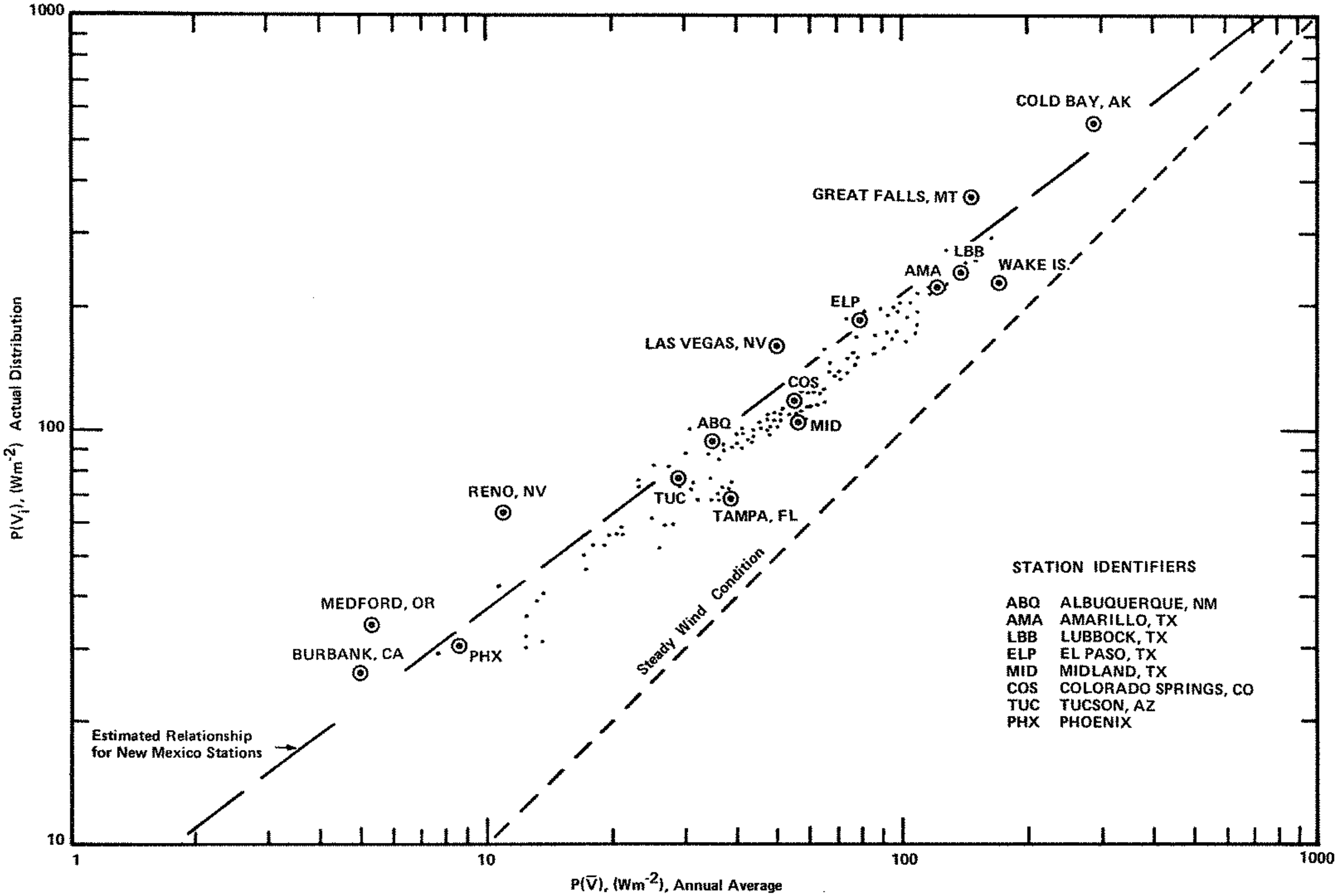

Figure 4. Comparison of Wind Power Calculated From Average Winds and From Actual Distribution

The method of Golding and Stodhart, which was derived for British stations, may not be suitable in New Mexico. An estimated relationship for New Mexico stations is shown by a dashed line through the Albuquerque point, following

$$
\begin{aligned}
P(V_i) &= 6.48\,[P(\bar{V})]^{0.763} \\
&= 4.47\,\bar{V}^{2.29}\ \mathrm{Wm^{-2}},\ \bar{V}\ \mathrm{m/s} \\
&= 0.707\,\bar{V}^{2.29}\ \mathrm{Wm^{-2}},\ \bar{V}\ \mathrm{mph} \\
&= 0.512\,\bar{V}^{2.29}\ \mathrm{Wm^{-2}},\ \bar{V}\ \mathrm{knots}\ . \qquad (3)
\end{aligned}
$$

This equation was used to calculate power values shown in Figure 3 for Roswell, Clayton, and White Sands.

The main belt of high wind power occurs over the northeast counties. This is an extension of a generally high wind power zone (Fig. 2) that extends south from Alberta, Canada, along the High Plains, and into northern Texas. The strong wind power value at Clayton apparently results from this wind stream being partially blocked by and pouring around the mountain ridge that spreads eastward along the Colorado border and through Raton Pass. To the east from Clayton, wind power drops in western Kansas and Oklahoma, where it averages around 250 $\mathrm{Wm^{-2}}$.

In central and western portions of the state average wind power falls to below 100 $\mathrm{Wm^{-2}}$. In preparing this wind power map, it was assumed that the somewhat higher general power pattern of northern Arizona and southern Utah and Nevada (Fig. 2) extended into the Four Corners area. Along the southern border of the state, the high-power region was assumed to extend southward through Chihuahua, but data were not available to confirm this. A high-power value at Guadalupe Pass, southwest of Carlsbad, was more or less ignored in contouring, because it was obtained from an observing station high on a ridge, operated to serve the east-west airway route to El Paso. This value should more properly be compared to the 518 $\mathrm{Wm^{-2}}$ power figure from Sandia Crest, east of Albuquerque, which was included in Table III.

An air-density correction factor, based on altitudes and average temperatures at the various stations, probably should be applied to these wind power figures. Some typical factors and corrected coefficients for Eq. (1) are shown in Table IV. Near 1200- to 1500-m (4,000- to 5,000-ft) MSL (mean sea level) altitude, power is reduced by about 15 percent for the annual average. There would be another 4-percent drop in summer and a 4-percent gain during colder winter temperatures. This density correction is equivalent to the effect of only a 30-percent reduction in anemometer height above ground (from 10 to about 7 m). The error from neglecting density bias is thus probably equal to or smaller than the likely uncertainty of anemometry data.

TABLE IV

Wind Power Corrections for Altitude and Temperature

Station	Elevation (m MSL)	Elevation (ft MSL)	Standard Pressure (kPa)	Average Temperature (K)	Average Temperature (°F)	Equation 1 Coefficient	Correction Factor
Clayton	1540	5054	84.1	285	54	0.04583	0.838
Tucumcari	1245	4085	87.2	288	59	0.04709	0.861
Roswell	1084	3557	89.0	288	59	0.04806	0.878
Albuquerque	1620	5314	83.2	286	55	0.04526	0.827
Zuni	1950	6400	80.0	283	50	0.04392	0.803
El Paso	1147	3672	88.3	290	63	0.04734	0.865
Sandia Crest	3255	10680	67.9	275	36	0.03852	0.704

On the other hand, it is not certain that installed anemometers were especially calibrated for the air density at their operating sites (see Slade,[29] p. 268). It is, therefore, quite likely that these gages may underestimate actual winds at higher altitudes, such as are found in New Mexico. Since the proper correction is not yet certain, it will be ignored in this report.

Wind power in the "free" air (above the boundary layer, where wind is slowed by ground surface friction) has been estimated from upper wind statistics. This wind power represents a goal to be aimed for in designing and siting collection systems. These data were obtained from weather balloon observations compiled by H. L. Crutcher, of NCC, in a U.S. Navy-sponsored project.[30] Analyses were made for standard levels used in preparing upper air weather maps. The statistical description model is shown in Figure 5 for spring months (March, April, May) at the 85-kilopascal (kPa) or 850-millibar pressure altitude level (near 1500-m MSL). Numerical values for the five necessary parameters, listed in Table V, were read from Northern Hemisphere maps provided for each parameter and each of the four seasons, at a point 35°N latitude, 105°W longitude, about halfway between Albuquerque and Tucumcari. A numerical integration for wind power across the elliptical normal distribution field was made to give the results in Table VI.

It appears that the "free" air carries roughly 4 times the power of the "surface" wind over much of New Mexico. Although the altitude of the 85-kPa level is below ground level in much of the state, statistical analysis and mapping techniques smoothed the original data on a very large scale. These results, therefore, are probably as representative as can be obtained.

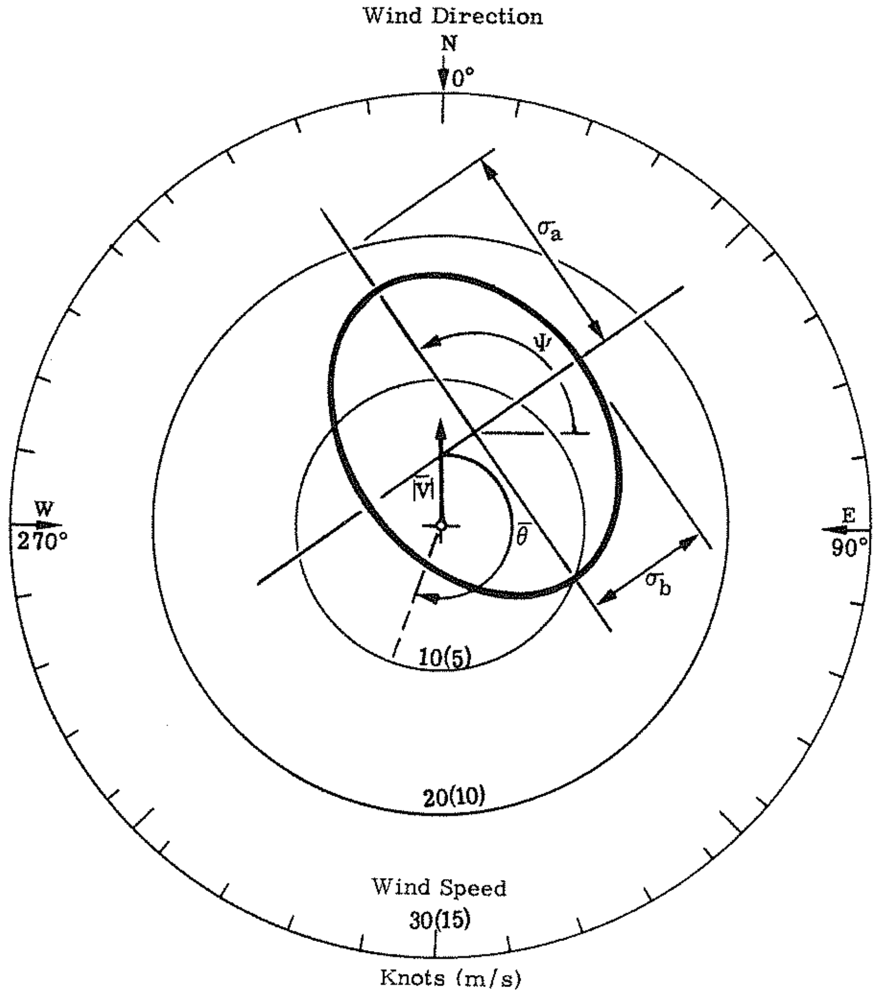

Figure 5. A Typical Upper Wind Rose of Vector Distributions, 850 mb, 35°N - 105°W, Spring Season

TABLE V

Upper Wind Statistics, 85 kPa, 35°N-105°W (from Ref. 30)

Parameter	Symbol	Seasons: Winter	Spring	Summer	Fall
Vector mean wind speed, m/s (knots)*	$\|\overline{V}\|$	2.6(5)	3.6(7)	4.1(8)	3.6(7)
Vector mean wind direction (degrees clockwise from north)	$\overline{\theta}$	180	200	180	170
Angle of rotation of major axis of wind distribution ellipse (degrees counterclockwise from east)	Ψ	20	125	90	90
Standard deviation of major axis component, m/s (knots)	σ_a	9.3(18)	6.2(12)	3.1(6)	5.7(11)
Standard deviation of minor axis component, m/s (knots)	σ_b	4.1(8)	4.6(9)	2.6(5)	4.1(8)

*1 knot (nautical mile, 6076 ft per hour) - 0.51 ms^{-1} = 1.15 mph.

TABLE VI

Wind Power at 85-kPa Pressure Altitude at 35°N-105°W

Season	Months	Average Wind Power (Wm^{-2})
Winter	Dec, Jan, Feb	666
Spring	Mar, Apr, May	451
Summer	June, July, Aug	115
Fall	Sept, Oct, Nov	419
Annual		419

Above the frictional boundary layer, the wind generally obeys the geostrophic equation, wherein the horizontal pressure gradient force is balanced by the Coriolis "force" of the earth's rotation at equilibrium. Usually this free-air flow condition is expected at about 150 to 450 m (500 to 1500 ft) above ground level. A study comparing surface wind reports with calculated geostrophic winds over a marine area (low friction) of the German Bight was recently reported by Hasse.[31] This showed that surface speeds were 0.517 to 0.566 times the geostrophic speed, which may be expected to prevail in the free-air flow. The coefficient increased with decreased stability. This would indicate, from inverse cubes of these factors, that geostrophic free-air flow contains from 5.5 to 7.2 times the surface flow power. However, 85-kPa statistics reviewed in preceding paragraphs did not indicate so large a difference. Neither analysis technique can be considered strictly appropriate in mountainous regions.

The problem in windmill site selection is, nevertheless, to approach this wind power potential in the free air by placing wind turbines as far above ground as is economically feasible or on selected terrain features which penetrate the relatively unobstructed upper flow.

Boundary-Layer Wind Effects

Friction at the ground surface slows the wind from the free-air value. The amount of friction depends upon surface roughness or obstructions and on thermodynamic stability of the air mass. Stability is determined by whether the temperature decrease with altitude is greater or less than about 0.01 K/m (3°C or 5.4°F per thousand feet). When temperature increases with height, as it often does at night on the desert, the air is very stable and the condition is called an "inversion." The depth of this boundary layer varies in a complex way, not yet well understood, with wind speed, surface roughness, and stability. Wind tunnel observations and aerodynamic theories that show its thickness decreasing with increasing wind speed are not strictly comparable to atmospheric conditions on a larger scale and where thermodynamic stability is so important.

In a more complete theoretical model both wind speed and direction change with altitude in the boundary layer, depending on stability, and follow an Eckman spiral. On the other hand, wind data show that a power law increase of speed with height is adequately descriptive for practical application.[21] This is expressed by

$$\frac{V}{V_o} = \left(\frac{z}{z_o}\right)^{\alpha} , \qquad (4)$$

where z is height above ground and zero subscripts refer to anemometer observation level. Modern references, such as Davenport,[32] show that the exponent often averages around $\alpha = 1/7$ over relatively flat terrain, but may equal or exceed $\alpha = 0.4$ in mechanical turbulence over rough terrain or in thermodynamically stable air masses. Golding[1] accepted earlier data that indicated $\alpha \approx 0.17$. The WMO study[21] indicated $0.25 < \alpha < 0.35$ "as the overall temperature gradient tends to become more stable."

Tower wind observations by the Sandia SMILE (Sandia Meteorological Instrumentation Logging System) network[33] have been evaluated to check the exponent, α, for this area. Seven 30-m (100-ft) and one 91-m (300-ft) towers, scattered around Albuquerque, were operated to obtain wind measurements at 3.7 m (12 ft) and 30 m (100 ft) above ground level. Measurements were also made at 61 m (200 ft) and 91 m (300 ft) on the tall tower. Observing sites and low-level wind power values are shown in Figure 6 on an Albuquerque map. The most apparent features of these power values are the high power obtained on Sandia Crest at 3255 m (10,680 ft) MSL, and the low power in the Rio Grande Valley bottom at SMILE Tower 6.

Results at 30 m above ground, shown in Figure 7, show a relatively uniform distribution except in the north valley and in Tijeras Canyon, Tower 5. The value at Tower 3 seems suspiciously low, but it may be a real consequence of the site located in lower Tijeras Arroyo. In general, it appears that the wind power at 30 m is nearly triple that at 3.7 m. Annual averages of power are plotted versus height in Figure 8 for each tower. These curves show about the same slope as the $V \sim z^{1/7}$ (or $P \sim z^{3/7}$) law in the first 30 m. Exceptions for Tower 5 in Tijeras Canyon and Tower 6 in the Valley can be explained by their particular exposures. Similar curves for each season showed that there was no significant seasonal variation in α that might be related to air mass characteristics. It might have been expected that these slopes would have been decreased in the hot, convective turbulence of July or increased by the mechanical turbulence of strong April winds. Also the cold, relatively stable air of January might have caused a slope increase, but none of these air mass characteristics appeared to have any effect on the monthly average. Of particular interest in Figure 8 is the fact that the 91-m tower result, 385 Wm^{-2}, is only 9 percent lower than the free-air power of the 419 Wm^{-2}, estimated from 85-kPa statistics in Table VI. This difference is about what would be expected for only 3-m height increase if $P \sim z^{3/7}$.

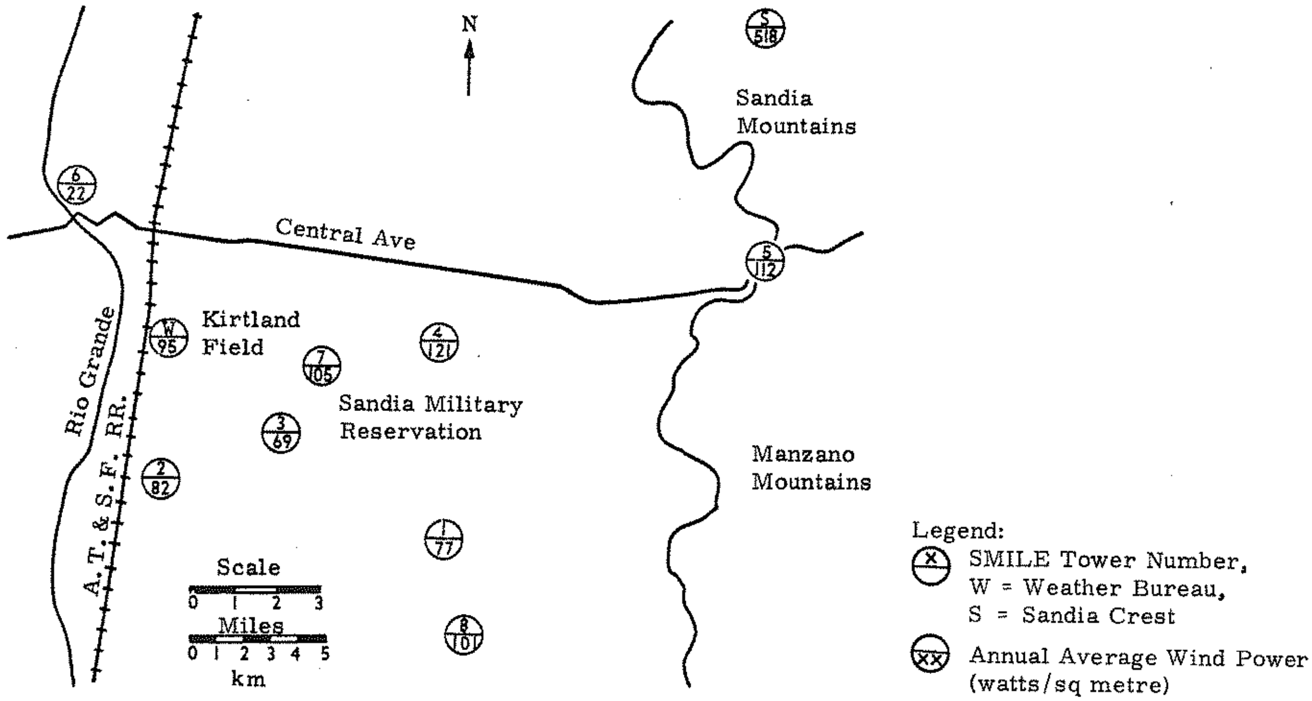

Figure 6. Annual Average Wind Power, 12-Ft Anemometer Heights, Albuquerque Area

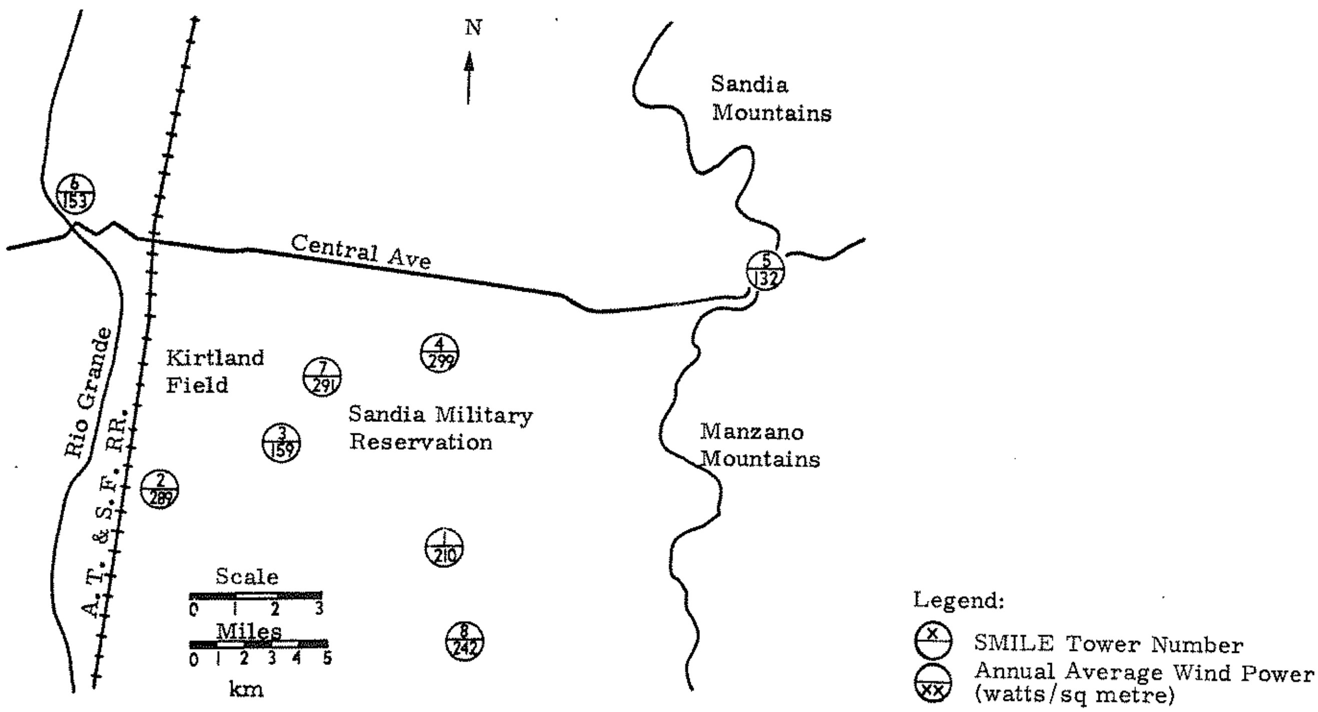

Figure 7. Annual Average Wind Power, 100-Ft Anemometer Heights, Albuquerque Area

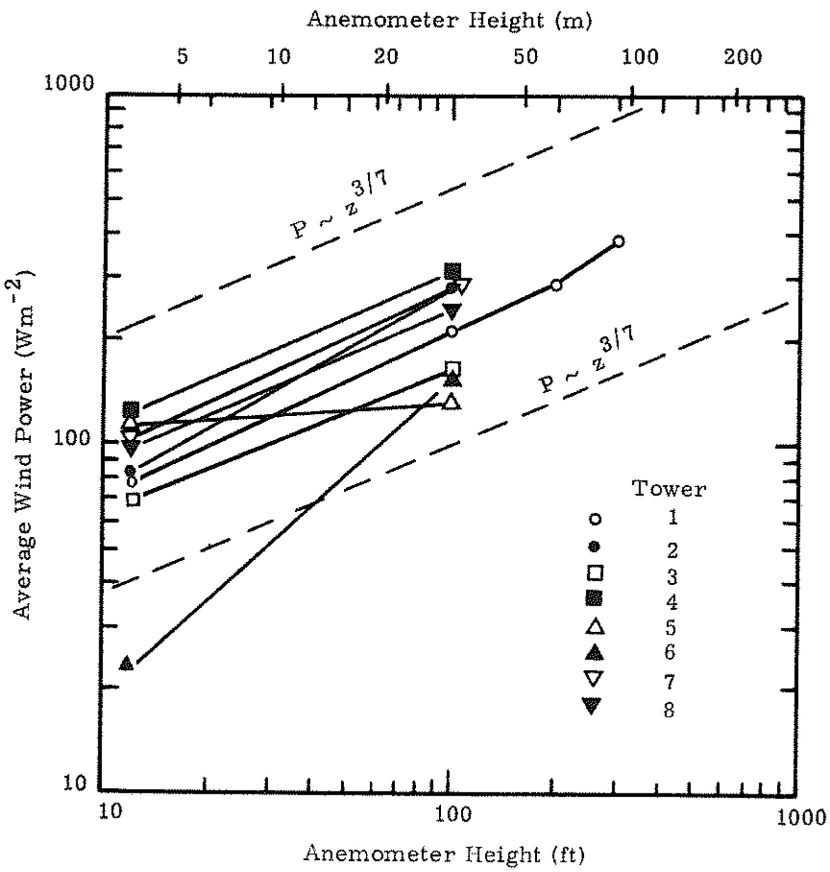

Figure 8. SMILE Tower Wind Power, Annual Averages

High-tower data to 61 and 91 m (Fig. 8) showed a small apparent slope increase aloft, which was unexpected. Ordinarily, mechanical turbulence is lessened with height, and a flattened slope might be expected. A comparable data collection[34] from Hanford, Washington, has been used to gain comparison height effects shown in Figure 9. Hanford results also show a significantly higher slope than the 1/7 law, averaging $\alpha = 0.18$, and approaching a parallel to the upper height data for Albuquerque. No confident explanation is offered at this time for this condition, which appears comparable to Golding's value,[1] but it may reflect mean thermodynamic stability in mountainous regions.

Hanford data were presented in a form suitable for further evaluation as a function of wind speed categories. Results, shown in Figure 10, clearly demonstrate that the power increase with height is greatest for light winds. The $z^{1/7}$ law does appear valid for wind speeds of about 11 m/s at the 15-m level. The apparent overall larger slope for Hanford annual averages may thus be a result of their lighter winds and somewhat lower average wind power than obtained at Albuquerque. It would also appear that mechanical friction is not a dominant consideration. At any rate, the $z^{1/7}$ law is found to be appropriate for New Mexico applications, particularly for the 4- to 13-m/s (10 to 30 mph) speeds of concern to most wind power collection systems.

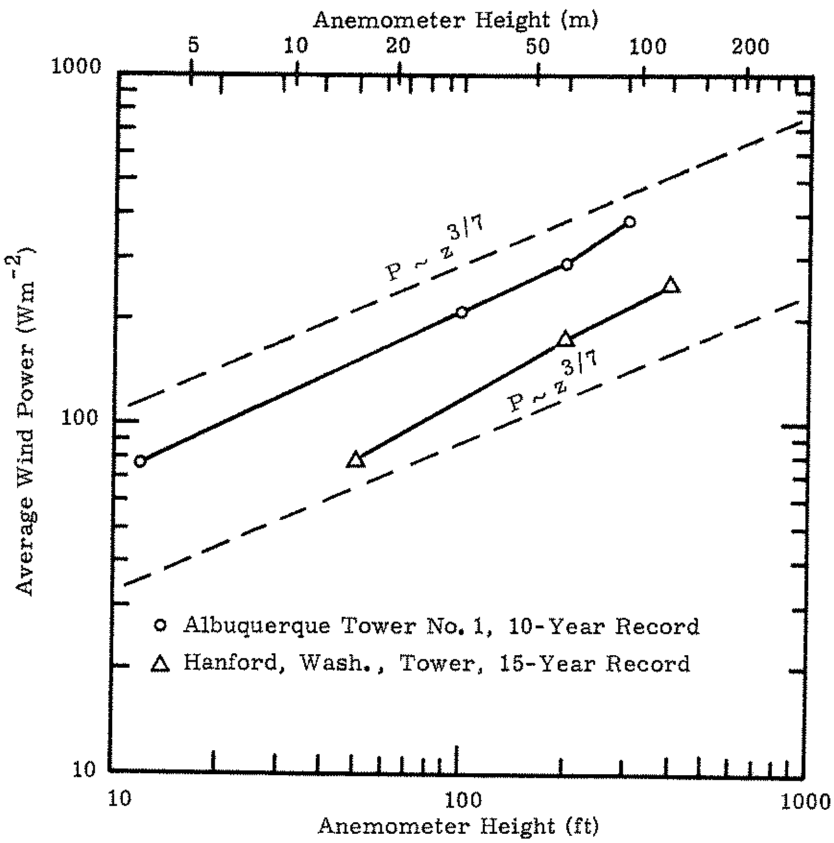

Figure 9. Wind Power Versus Height in Albuquerque, New Mexico, and Hanford, Washington

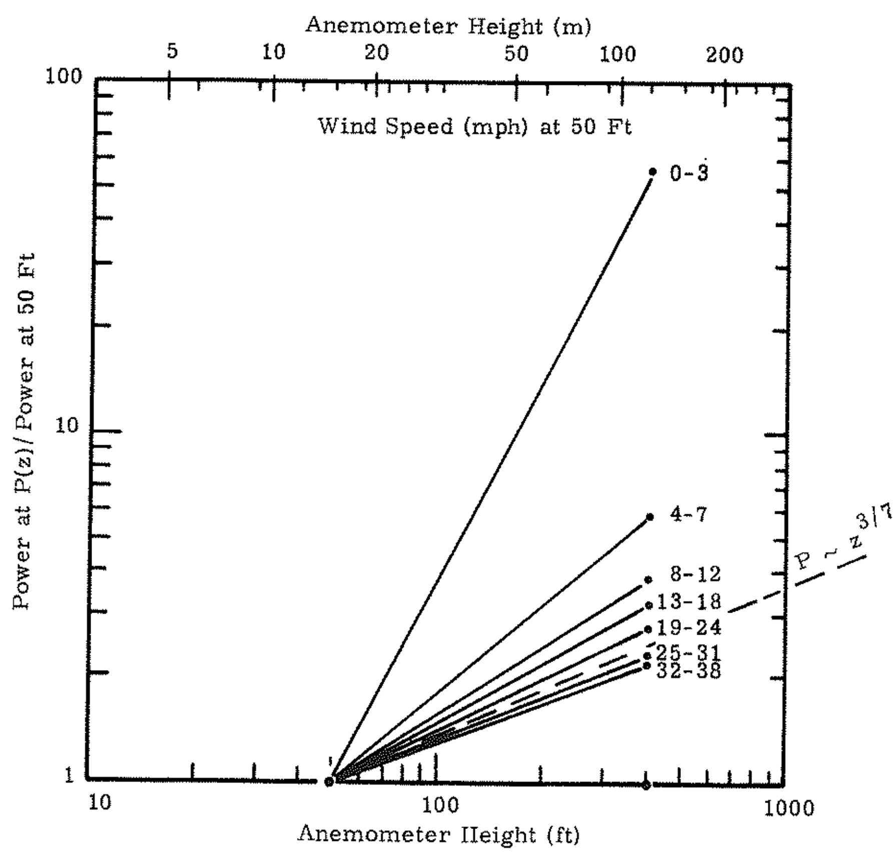

Figure 10. Wind Power/Height Comparisons by Wind Speed Categories, Hanford, Washington, 15-Year Data

A relevant report by Hansen,[35] from White Sands Missile Range, considered 1-hour mean wind speeds versus tower anemometer height for various thermodynamic stability regimes. Speed-versus-height curves are shown in Figure 11. Even though wind speeds were higher under the most stable test condition, the slope of the curve is slightly greater than under unstable conditions. Unfortunately, these data could not be analyzed to show temperature stability effects under constant wind speed conditions. Another White Sands study[36] showed wind speed increase with height for "stable" and "unstable" conditions, with results compared to the $z^{1/7}$ law in Figure 12 again showing a larger slope with larger stability.

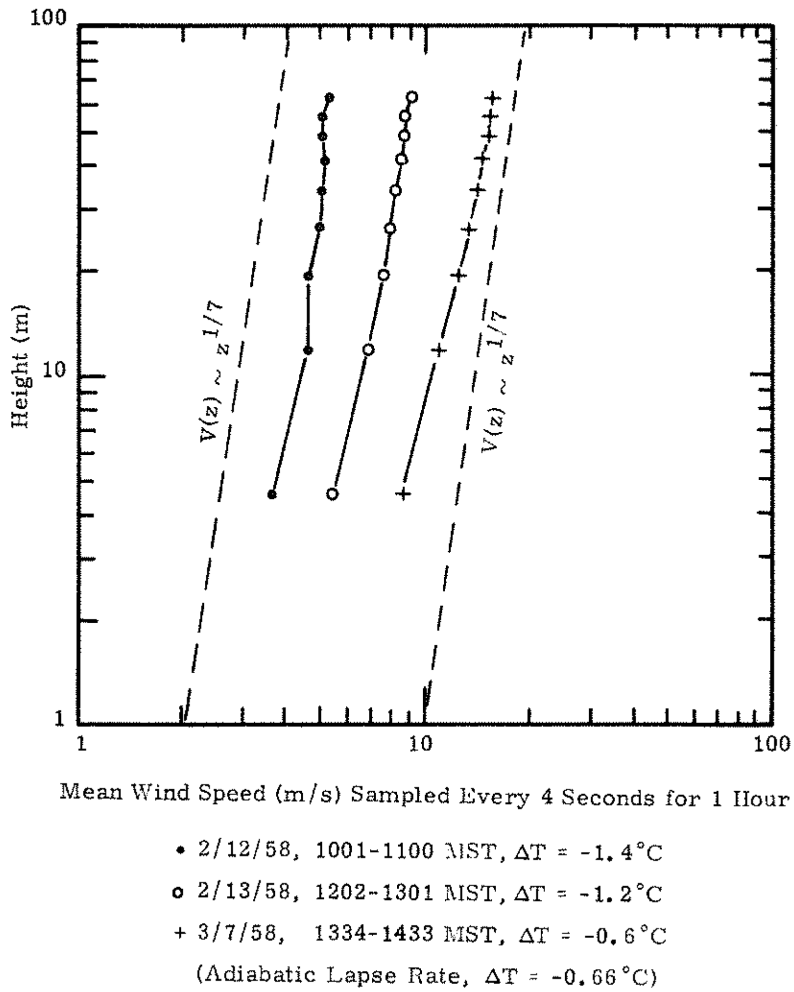

Figure 11. Wind Speed Versus Height and Temperature Drop at White Sands, New Mexico (from Ref. 35)

In summary, and until detailed site survey data for particular places are obtained, the power law increase of speed with height with the exponent $\alpha = 1/7$ appears adequate for planning purposes in New Mexico.

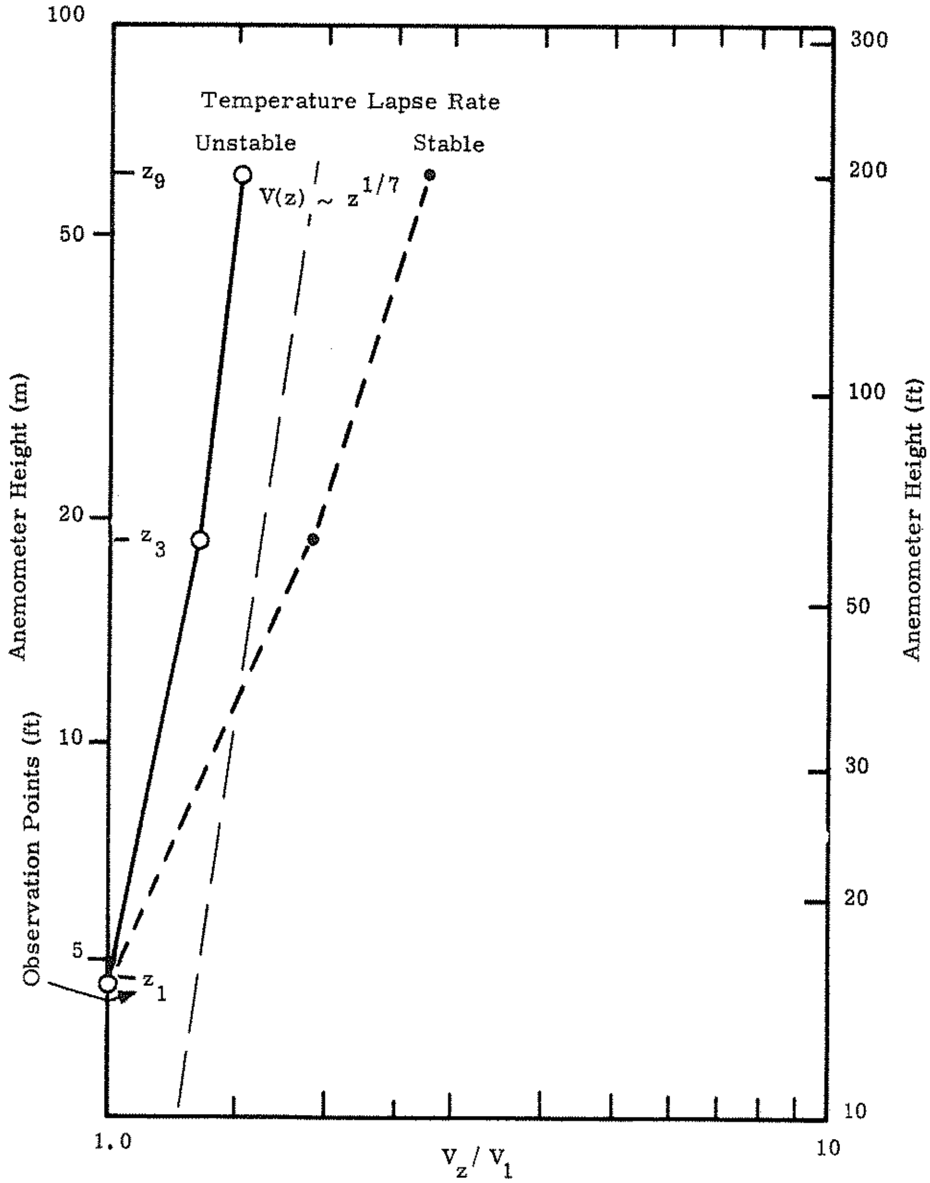

Figure 12. Wind Speed/Height Relationships Under Stable and Unstable Thermodynamic Conditions

Potential Wind Turbine Arrays

A simplified analysis model for a vertical-axis wind turbine has been used to estimate power available from various sites, as diagramed in Figure 13. Aerodynamic effectiveness of the blade varies with position as does differential swept-area increment. These factors have been used with the wind-speed-versus-height relationship to obtain the intercepted power, P_I, from

$$P_I = k\left[V(R+S)\right]^3(\pi R^2)\int_0^2 \left(\frac{z}{R}+\frac{S}{R}\right)^{3/7}\left\{\left[2\left(\frac{z}{R}\right)-\left(\frac{z}{R}\right)^2\right]^{1/2}\cdot \epsilon\left(\frac{z}{R}\right)\cdot d\left(\frac{z}{R}\right)\right\}. \qquad (5)$$

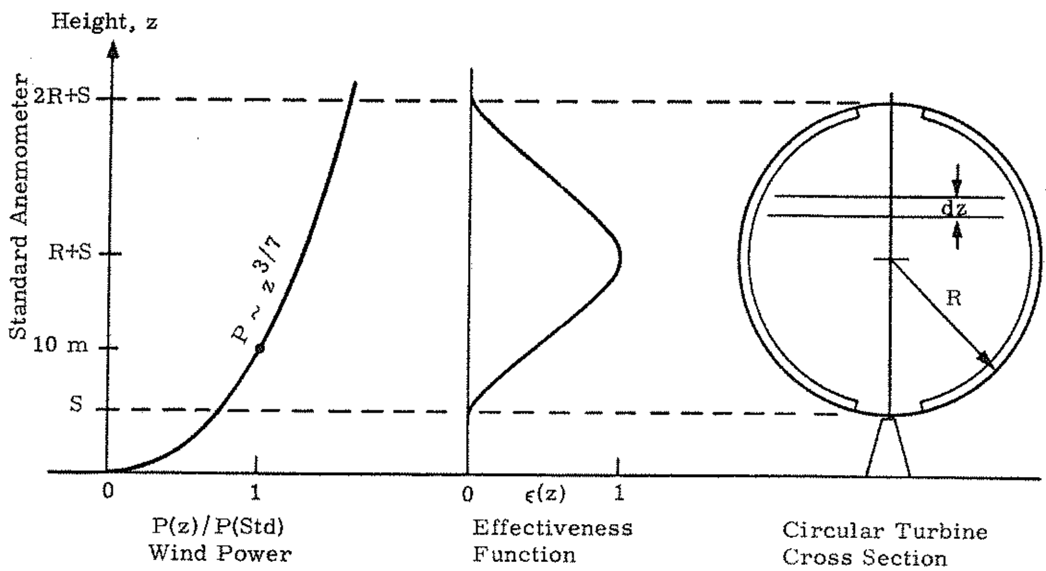

Figure 13. Diagram for Height Effects Evaluation

Numerical values for the net effectiveness, including swept area and shown inside the brackets of Eq. (5), have been used to illustrate that use of the wind speed at the center of the turbine, at height R + S, radius plus base height, causes only a minor (4 percent) overestimate of intercepted power. On the other hand, mounting on a pedestal of even 0.1R height more than overcomes this loss. About 10-percent power gain obtains with a 0.2R pedestal height, and this may be necessary for safe access under the rotor, but the 0.1R pedestal will be assumed for subsequent calculations to be conservative.

In addition, the power extraction efficiency for windmill blades is often assumed to be about 40 percent.[1] The theoretical limit for a horizontal-axis turbine is 16/27, according to Betz.[37]

In consequence, the estimate of extracted power, P_E, used here is

$$P_E \approx (0.4)(\pi R^2)\left(\frac{R}{10}\right)^{3/7}(P_{10}) = 0.468\, R^{17/7}\, P_{10}\,, \qquad (6)$$

where P_{10} is calculated wind power, based on wind speed at a standard anemometer height of 10 metres. Some power production estimates calculated from Eq. (6) are shown in Table VII.

TABLE VII

Power Production Estimates at Selected New Mexico Sites

Location	Approximate Annual Average Wind Power (Wm^{-2}) at 10-m Height	Average Extracted Power (kW) for Turbine Radius			
		5 m	10 m	20 m	40 m
Albuquerque	100	2.3	13	68	364
Clayton	300	7.0	38	203	1092
Sandia Crest	500	11.7	63	338	1819

These estimates need comparative evaluation in terms of per capita electric power consumption. According to figures quoted by AEC Chairman, Dixy Lee Ray,[38] United States electric production capacity is about 4×10^{12} kWh/yr, but only about 40 percent of this capacity (1.6×10^{12} kWh/yr) was consumed in 1972. Consumption averages around 180×10^6 kW, or about 0.8 kW per person. Of this, probably 20 percent is consumed by residential usage. If it is assumed that efficient (100 percent) energy storage systems were available, then a large (40-m radius, 80-m-diameter (262 ft)) turbine on Sandia Crest could provide for the residential electric consumption of 11,000 people. Twenty-six such units would be needed to serve Greater Albuquerque's 300,000 population. These would form a line for 2 km (1.3 miles) along the ridge if it is assumed that they need not be spaced at 8-diameter intervals as suggested by Golding.[1]

In New Mexico in 1971, the estimated population of one million consumed 5.21×10^9 kWh of electricity, according to Public Service Company figures,[39] averaging 0.593 kWh per person. The Bernalillo County population of 322,000 in 1975 would use 190 MW for all purposes—residential, commercial, and industrial—if this rate of consumption continues. Serving this consumption would require 104 of the 40-m radius turbines, extending over 8 km (5 miles) of the ridgeline. This would no doubt generate considerable environmentalist opposition, but it is within the realm of possibility. If it is assumed that a double row is neither possible nor efficient, use of smaller (20-m)rotors would, of course, necessitate more than 5 times as many units, spread along 2.7 times as long a line.

Energy storage would be required for power extracted from strong winter and spring winds to last through the light wind period of summer months, shown in Figure 14. The ragged character of the monthly data curve may be real, judging by the April peak, but most probably a longer record would smooth the pattern, as shown by the dashed curve, through seasonal means. Also, since Sandia Crest power estimates are nearly the same as for Guadalupe Pass, Texas, it would appear that any fairly large ridge in New Mexico would offer comparable wind power.

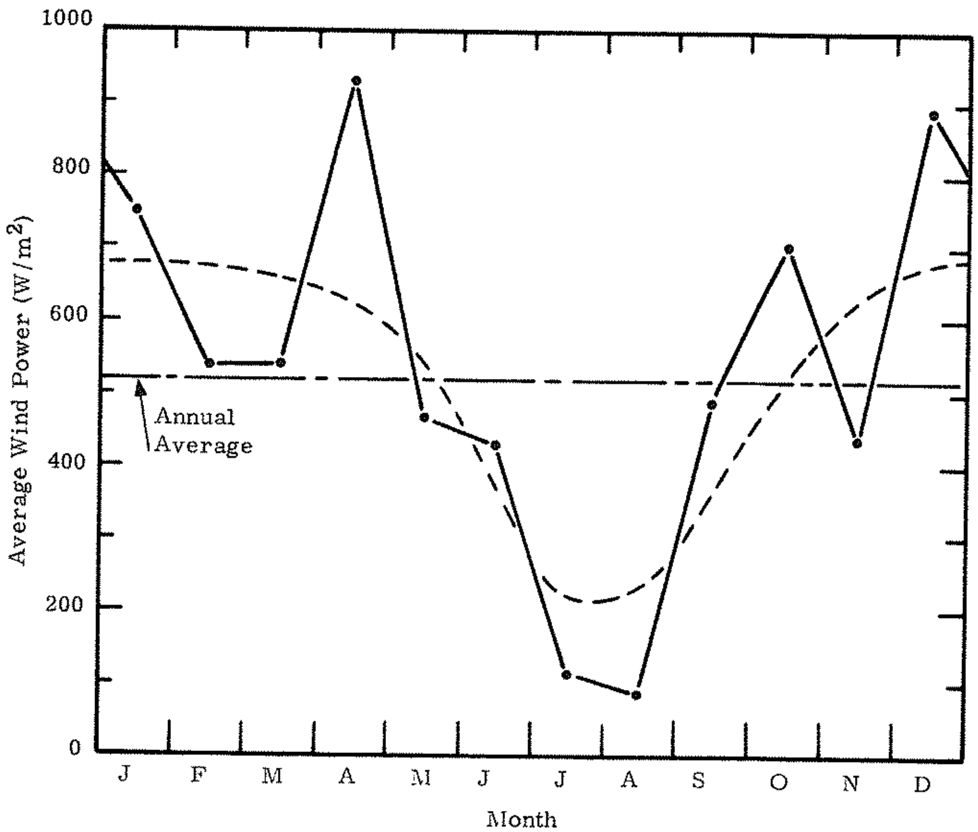

Figure 14. Monthly Averages of Wind Power at Sandia Crest

A proper evaluation of downstream effect, leading to spacing criteria designed specifically for wind turbine fields, should eventually be made. For the moment, however, a simplistic model may suffice to show that 8-diameter downwind spacing, suggested by Golding,[1] is not warranted. As power is extracted from the wind by a vertical-axis turbine (see Fig. 15), the disturbance will be smoothed out by turbulent mixing of energy brought in from the surrounding undisturbed flow. Since only about 40 percent of the wind power passing through a circular cross section perpendicular to the wind is removed, there would be a net 10-percent reduction only 2 or 3 diameters directly downstream. Thus, to conserve occupied land area and connecting cable lengths, it would appear that relatively close packing of turbine rotors could be feasible without serious losses.

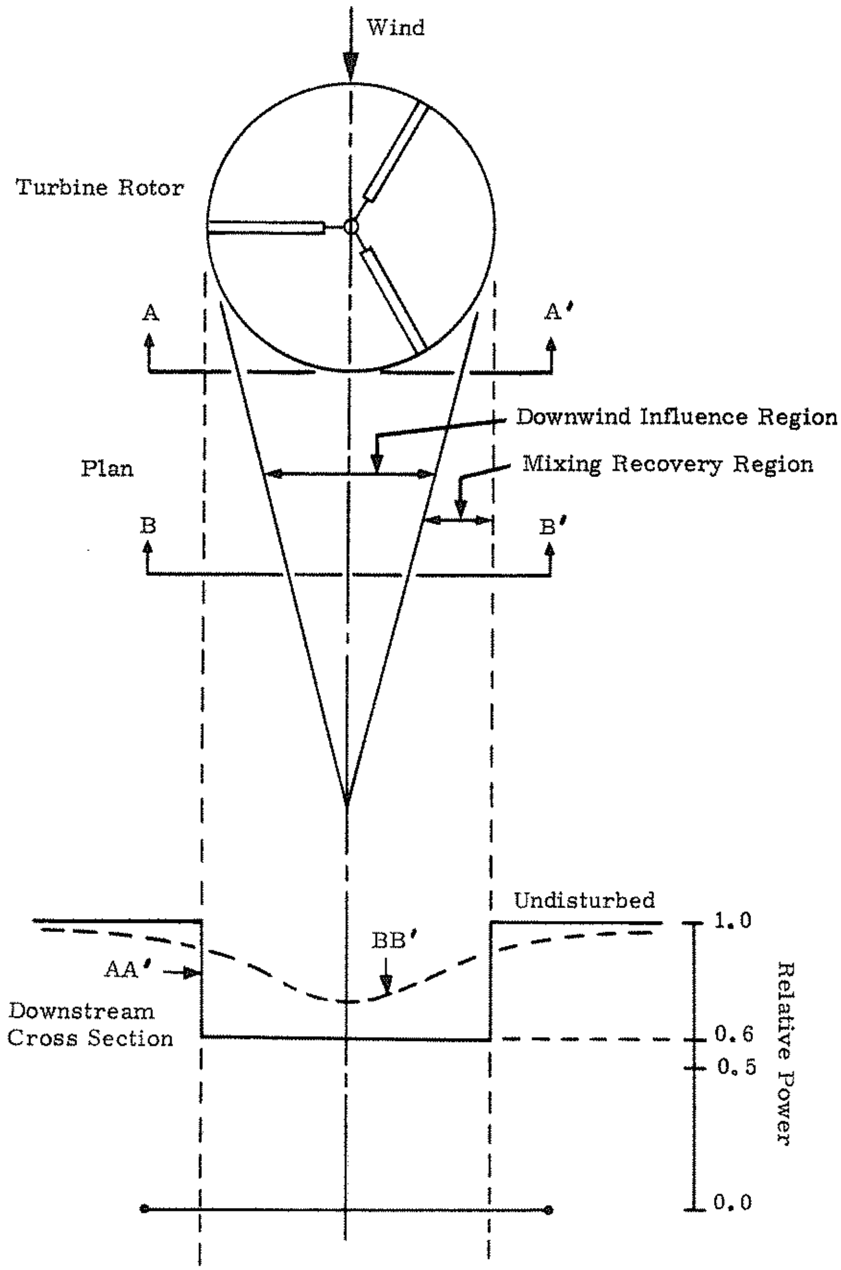

Figure 15. Diffusive Recovery of Wind Power

The border of the recovery region, shown in the Figure 15 plan view, is not a clearly defined surface. Instead, it is shown as the locus of 1σ (standard deviation) in a one-dimension diffusivity model for contaminant dispersion.[29] A horizontal diffusivity coefficient,[40] $K_h = 300\ m^2 s^{-1}$, was used with a typical interesting $10\text{-}ms^{-1}$ wind speed to generate the 14° convergence angle. A two-dimension treatment is certainly required, but more reliable diffusivities, both horizontal and vertical, need to be obtained for some specific sites, in order to justify more detailed calculations. In particular, credible diffusivity measurements in mountainous terrain are rare, if they exist at all. Furthermore, these coefficients should be obtained under those wind conditions which produce useful power levels. Most data collections[40] to date have been primarily concerned with contamination-dispersal problems, so that concerns with light winds and related thermodynamic stabilities have almost totally absorbed the interests of researchers. Their results probably have little bearing on windmill spacing problems.

A hexagonal-grid turbine field with 1-diameter blade separations is shown in Figure 16. Axis spacing along a line is 4R, and line spacing is $4R \cos(\pi/6) = 3.464R$. The hexagonal area allocated to each turbine is $13.856R^2$. If boundary constraints were neglected, one section of land (1 square mile, or $2.59\ km^2$) could be planted with 117 units with 40-m-radius blades, or with 467 units with 20-m-radius blades.

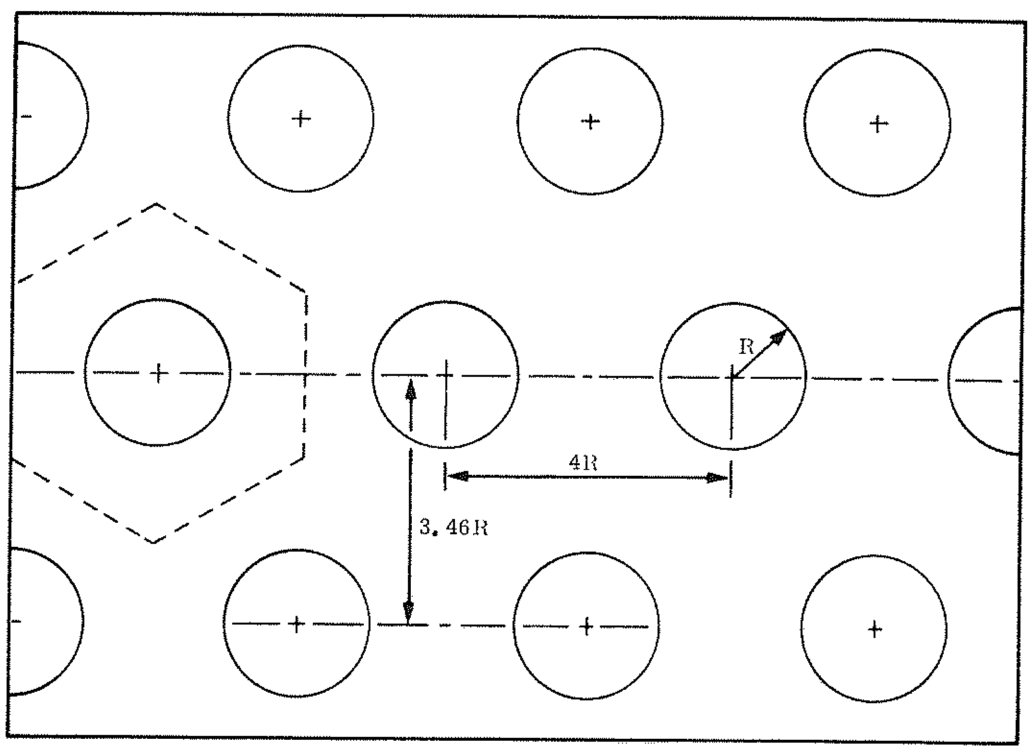

Figure 16. Plan for Wind Turbine Field

Near Clayton such a field would produce (see Table VII) 128 MW with 40-m-radius systems, or 95 MW with 20-m-radius systems, if downstream losses could indeed be neglected with assumed spacing. This would serve the needs of 120,000 to 160,000 people, according to national average electric power consumption statistics which include all commercial and industrial users. On the other hand, near Albuquerque, where the average wind power appears to be only one-third as great, it would take almost 6 square miles (15 km^2) of 40-m-radius turbines to produce enough electric power for the population share of national consumption. Actual New Mexico consumption figures would reduce the areal requirement by 20 percent. These turbines would not interfere with the small amount of grazing being conducted in the area. In fact, by partial shading and wind speed reduction, the turbine field would cut evapotranspiration water losses, so that there would be more vegetation and cattle feed.

At any rate, it would appear that the total environmental impact in terms of used-land area, or producing electric power by windmills to meet the needs of New Mexico, is certainly no greater than that from conventional systems. Those areas now totally occupied by coal strip mines and reservoirs—as well as natural gas and petroleum producers, electric generating plants, and power transmission lines—would appear to be much larger.

Economic Considerations

The Public Service Company of New Mexico estimated current (1973) installed costs of natural gas and oil or coal electrical generating plants at $148 and $277/kW, respectively.[39] Installed cost of nuclear power plants is in the range of $300 to $500/kW, but will rise to over $700/kW for plants now being constructed[41] for operation by 1982. The 1945 installed cost of the 1.25-MW Vermont windmill was about 50 percent greater than hydroelectric power in Vermont, which was then $125/kW. Capital costs[7] of the 1957 Danish (Gedser) 200-kW system was $210/kW. Estimated costs (1974) for the 100-kW NASA Plum Brook, Ohio, facility are about $1000/kW for the prototype, with cost reductions to $500/kW as a design goal for larger production units. The Canadian NRC team[13] indicates that its vertical-axis turbine could be produced at costs as low as one-sixth the cost of the conventional horizontal-axis turbine.

Revenue to private utilities averaged slightly more than 2 ¢/kWh in 1969 for residential and commercial companies and 1 ¢/kWh (36 percent of total sales) for industrial companies. The estimated operating costs of the Vermont windmill (1945) was 0.7 ¢/kWh; of the Gedser, Denmark, windmill (1957), was 0.4 ¢/kWh. NRC[13] has estimated 1974 operating costs of the vertical-axis turbine at 1.7 to 2.6 ¢/kWh for an average wind velocity of 10 mph (6 m/s); these costs would scale down to 0.8 ¢ to 1.2 ¢/kWh for an average wind velocity of 15 mph (9 m/s).

Hence, a preliminary look indicates that the installed cost of wind turbine generator power plants (for carefully selected wind sites) should be competitive with nuclear power plants today and fossil-fuel power plants of the future if fuel costs continue to rise.

Concluding Remarks

In this report, an attempt has been made to show that there is considerable promise to schemes for collecting power and energy from New Mexico winds. Competitive, cost-effective wind turbine construction and operation will depend, however, on site selection, relatively inexpensive construction, and suitable energy storage. New Mexico is not particularly windy, when compared to the Great Plains or certain ocean areas, but it does have a fairly good wind-power potential (except in summer months), adequate to serve in excess of any conceivable local electricity needs without unconscionable environmental insult. Efficient extraction of this energy, according to tentative climatological data, would appear to require wind turbine fields either in the northeastern plains counties or along some of the medium-sized mountain ridges, such as Sandia Crest. Wind turbine sites in many canyon or valley communities would be essentially useless.

Power production for export, however, does not appear to be economically attractive, by contrast with our situation in regard to gas, oil, and coal energy sources. There are other regions—such as Wyoming and Montana, or even Kansas, Oklahoma, and Texas—where more wind power is generally available and at reduced operating costs. If this energy could be packaged in hydrogen or exotic fuel cells, as opposed to power line transmission, wind energy might best be collected in either the stormy parts of the globe—such as the Aleutian Islands—or in the more persistently windy tropical trade wind belts.

For the present, however, and with a continued power line network for energy distribution assumed, it appears that wind turbines could be used to augment fossil-fuel-burning generator plants during almost 10 months of the year to conserve irreplaceable fuels.

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