ECONOMIC ANALYSIS OF WIND-POWERED CROP DRYING

Final Report
March 1980

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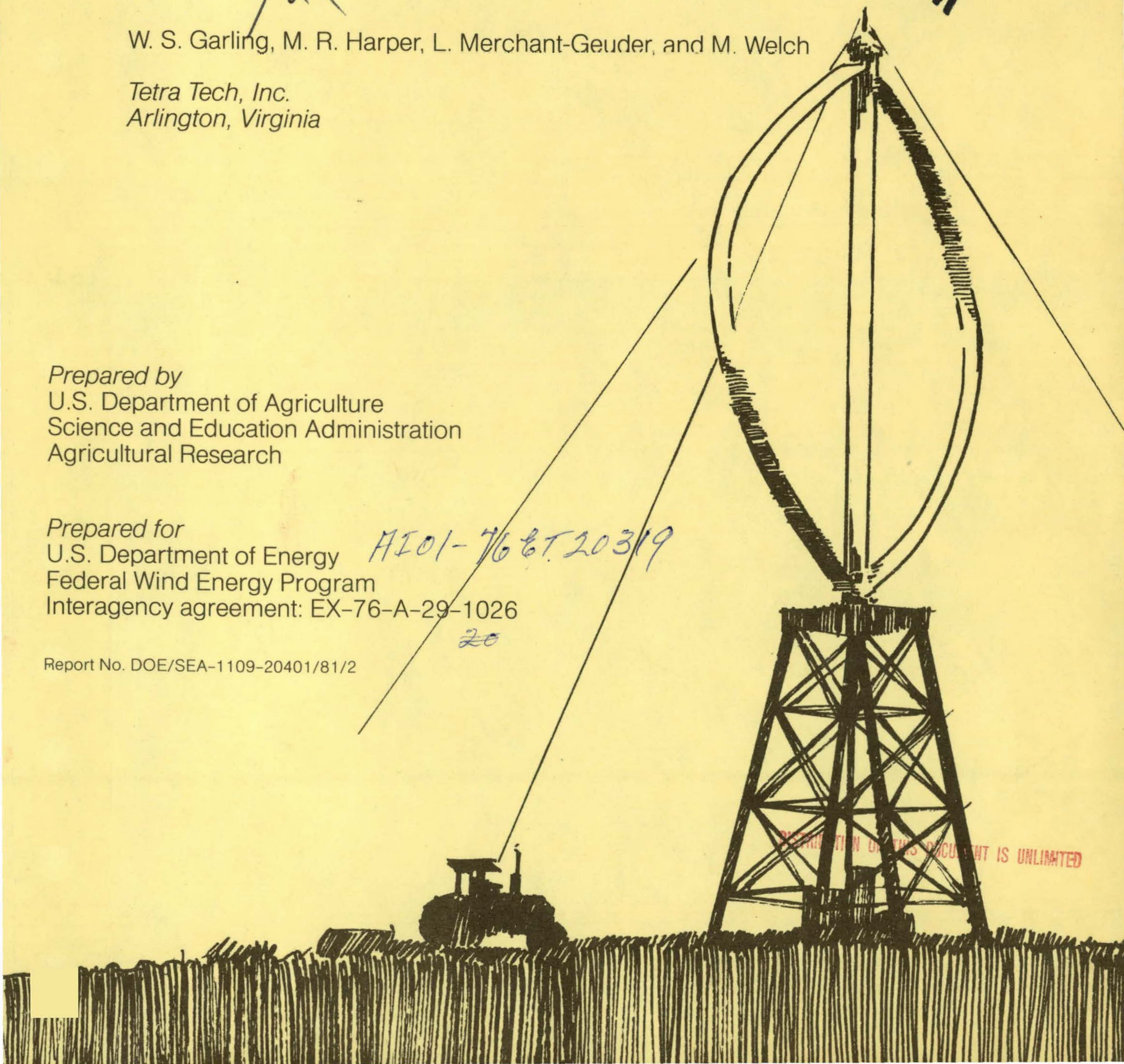

Prepared by
U.S. Department of Agriculture
Science and Education Administration
Agricultural Research

Prepared for
U.S. Department of Energy
Federal Wind Energy Program
Interagency agreement: EX-76-A-29-1026

Report No. DOE/SEA-1109-20401/81/2

DISCLAIMER

Report No. DOE/SEA-1109-20401/81/2, printed April 1981.

DOE/SEA-1109-20401/81/2
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MARCH 1980

Prepared For
Science and Education Administration
US Department of Agriculture
Beltsville, Maryland 20705

Contract No. 53-32U4-9-181

As a Part of The
US DEPARTMENT OF ENERGY
DIVISION OF DISTRIBUTED SOLAR TECHNOLOGY
WIND SYSTEMS BRANCH

Interagency Agreement EX-76-A-29-1026

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ABSTRACT

Potential applications of wind energy include not only large central turbines that can be utilized by utilities, but also dispersed systems for farms and other applications. The U.S. Departments of Energy (DOE) and Agriculture (USDA) currently are establishing the feasibility of wind energy use in applications where the energy can be used as available, or stored in a simple form. These applications include production of hot water for rural sanitation, heating and cooling of rural structures and products, drying agricultural products, and irrigation. This study, funded by USDA, analyzed the economic feasibility of wind power in crop drying. Drying of corn, soybeans, rice, peanuts, tobacco, and dehydrated alfalfa were addressed.

The methodology involved (1) describing equipment and procedures used in crop drying, and describing and estimating energy requirements for drying systems; (2) making an inventory of crop dryers, by state; (3) analyzing wind patterns on both an annual and seasonal basis, and comparing crop dryer locations with wind availability; and (4) performing an economic analysis. The economic analysis included a determination of the breakeven costs of small wind energy conversion systems required to economically supplement or replace present energy sources, an estimation of payback periods, and comparison of breakeven costs with projected wind system costs.

A major conclusion of the study was that the economics currently are not favorable if wind systems are operated only for crop drying, since drying is a seasonal activity often occurring for only 6 to 8 weeks in the fall. Breakeven costs would not be achieved if currently projected wind system costs are assumed. However, if these systems were to supply electricity for farm uses other than crop drying, their installation seems economically viable. They should find the greatest use in low-temperature drying of grains and peanuts, where dryers are operated over relatively long periods of time but require little heat. Even if breakeven costs were to be achieved, the payback periods estimated were fairly long--between 9 and 12 years.

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EXECUTIVE SUMMARY

Substantial amounts of the grain and other crops produced in the United States now are dried using artificial heat and ventilation, rather than being dried naturally in the field. Crop drying is energy intensive: in 1974 a total of 77 million gallons of fuel oil, 664 million gallons of liquid petroleum gas, 27 billion cubic feet of natural gas, and 858 million kilowatt-hours of electricity were consumed (110,000 terajoules). The purpose of this study was to determine to what extent conventional energy sources used in crop drying can be supplemented or replaced by wind energy.

The methodology involved: (1) describing equipment and procedures used in crop drying, and describing and estimating energy requirements for different sizes and types of drying systems. Crops were restricted to corn, soybeans, rice, peanuts, tobacco, and dehydrated alfalfa; (2) an inventory was made of crop dryers by state; (3) wind patterns were analyzed on an annual and seasonal basis, at three different heights, and locations of crop dryers were compared with wind availability and; (4) an economic analysis was performed to determine breakeven costs of small wind energy conversion systems (SWECS) required to economically supplement or replace present energy sources, estimate payback periods, and compare breakeven costs with projected SWECS costs.

Equipment, Procedures, and Energy Use

Crop-drying energy requirements vary according to type of crop, amount of production, and parameters such as initial and desired moisture content and ambient air temperature and humidity. High-temperature, high-capacity grain dryers, which include continuous flow and batch dryers, have high energy requirements. Temperatures in continuous flow dryers range up to 121°C (250°F); batch drying temperatures are between 49° and 93°C (120° to 200°F). Electricity requirements for fan operation also are substantial. The trend in the Midwest is toward lower temperature drying, with temperatures between 27° and 38°C (80° to 100°F). Total energy required is reduced, although electricity costs are usually higher because of a longer period of fan operation. These systems can be operated with electricity only for a low temperature rise. Other drying procedures with relatively low energy requirements include (1) combination drying, where grain initially is dried in a high-temperature system, then cooled slowly with low-temperature air; and (2) dryeration, in which it is dried to an intermediate moisture content, then "tempered" with low-velocity air circulation.

Continuous flow rice dryers use a 21° to 54°C (70° to 130°F) temperature lift, while peanut drying requires an increase of only about 11°C (20°F). Most kinds of tobacco curing require temperatures of up to about 79°C (175°F), raised in stages over a period of up to 150 hours. Alfalfa dehydration is high-temperature drying, with the product leaving the drum at about 77°C (170°F).

Natural gas, LPG, or fuel oil supply heat to dryers, while electricity operates the fans, or motors in dehy facilities. Estimates were made of the seasonal energy requirements of different sizes and types of dryers: grain-drying fossil fuel requirements were estimated to range from a low of nearly 20,000 cubic feet of natural gas, or about 200 gallons of LPG, for a 2,000-bushel (bu) low-temperature in-bin system; to nearly 40 million cubic feet of natural gas (456,000 gallons of LPG) for a continuous flow system handling 3 million bu. Electrical requirements range from 520 kilowatt-hours (kWh) for a 7,500-bu batch dryer to 120,000 kWh for the large continuous flow. A low-temperature system using electrical heat only was estimated to require 1,340 to 3,400 kWh for 2,000 bu. Rice dryers have heat energy requirements under one-fifth of those used to dry the same amount of grain, and use slightly less electricity. To dry an average yield from 52 hectares (128 acres), or about 3,840 hundredweight, a peanut dryer requires about 120,000 cubic feet of natural gas (1,400 gallons of LPG), and around 4,300 kWh. Depending on type barn and other parameters, tobacco curing consumes between 1,400 and 3,000 gallons of LPG (or 800 to 1,760 gallons of fuel oil) and 360 to 540 kWh. Good data were not available for estimating forage requirements; guesstimates for 1,000 tons were nearly 12 million cubic feet of natural gas and 125,000 kWh.

Crop Dryer Inventory

Estimates of numbers of crop dryers were based on data obtained from state crop-reporting services and universities. In some states (e.g., Illinois), surveys of grain-drying equipment have been undertaken. Estimates of grain-drying facilities in the Midwest probably are reasonably accurate. However, fewer data are available for grain dryers in other areas and for other types of dryers.

Crop-drying facilities are most numerous in the midwestern and southeastern states. The largest grain-producing and grain-drying region is the Midwest. Those midwestern states with the largest estimated numbers of drying facilities include Illinois (about 70,000), Iowa (60,000), Missouri, Minnesota, and Indiana (close to 30,000 each). The southeastern states, particularly North Carolina, also produce and dry substantial quantities of grains; several drying facilities are located in the middle-Atlantic states, and a few in the West. In addition, rice is dried in the southwest and south-central regions. Although many grains are dried artificially, by volume corn and soybeans are the most important. Rice production is less than that of corn and soybeans, but very nearly all rice now is artificially dried.

Peanuts are grown and dried in the Southeast, some middle-Atlantic states, and the southwestern states of New Mexico, Oklahoma, and Texas. Tobacco curing occurs predominantly in the Southeast, the middle-Atlantic, and the midwestern states of Indiana, Missouri, Ohio, and Wisconsin. Shade tobacco is grown in Connecticut. Although forages no longer are dried artificially to any great extent, because of the energy expense, several alfalfa dehydration facilities still are operated. States with the largest numbers of dehy operations include Nebraska, Kansas, and California. A few of these facilities also are located in most other parts of the country (except the Southeast).

Wind Pattern Analysis

To show the availability of wind power for crop-drying, wind contour maps were prepared. These maps show areas with annual average wind power density of 100 watts per square meter (W/m^2) at 10, 20, and 50 meters (m) above ground. 100 W/m^2 was chosen as the cutoff point below which wind power would be unlikely to produce useful power economically.

The analysis of mean annual wind power indicated that, in general, the midwestern states that are large producers of corn, soybeans, and alfalfa dehy are good candidates for wind-powered drying systems, as are the southwestern states producing rice and peanuts. At least half the areas of these states have wind power of at least 100 W/m^2 at 20 m (50 m is probably too high for small turbines to be used for farm applications). The wind resource is extremely limited in the Southeast, however, where much of the country's tobacco, peanuts, rice, and corn are grown.

The seasonal availability of wind power in many regions does not coincide with crop-drying requirements. Winds generally are best in winter and spring, while most crops are dried in the fall. However, several stations in the midwestern and southwestern crop-drying areas do record wind powers of over 100 W/m^2 at 20 m during the fall crop-drying months. The tobacco-curing season is particularly ill-suited to take advantage of wind power, since it usually includes the relatively calm month of August. Production of dehydrated alfalfa also occurs during the summer (from late spring into fall) in most areas. Wind systems still might be operated on a supplemental basis for only a part of the crop-drying season.

Economic Analysis

The objective of the economic analysis was to derive the maximum price a user should be willing to pay to purchase SWECS for use in crop-drying applications (breakeven cost) and to compare this price with currently projected prices of wind machines. Seasonal costs for several crop-drying systems were derived, using the most recently available national energy prices. Electricity for crop drying was assumed to cost 4.12¢/ kWh, the 1978 average revenue per kilowatt-hour of Rural Electrification Administration borrowers operating distribution systems for small commercial industrial establishments. This price is between the average retail electricity prices listed by the Department of Energy for residential (4.91¢/kWh) and industrial (3.11¢/kWh) establishments in July 1979. The natural gas price (198.8¢ per thousand cubic feet) was the average price to industrial users as of July 1979. Two LPG prices were assumed: the July 1979 average wholesale (29.3¢ per gallon) and residential (48.2¢ per gallon) prices. The latter was closer to prices assumed in recent crop-drying studies, which ranged from 40 to 54¢ per gallon. The July 1979 average wholesale price of fuel oil No. 6 (45.7¢ per gallon) was used.

Present values of the seasonal energy costs of cropdrying operations (the present value of the benefits or savings if these conventional energy sources were to be replaced) were calculated over a period of 20 years (assumed SWECS lifetime), with a 10 percent discount rate. Fossil fuel costs were assumed to escalate at a rate of 35 percent for the first 2 years and at 8 percent annually thereafter; electricity costs were assumed to rise 20 percent annually for the first 2 years and at 4 percent per year thereafter. These rates of increase were specified by USDA and DOE personnel, and represent the rate of increase of fuel and electricity costs above inflation.

From the resulting present values, the allowable investment cost or breakeven cost for the SWECS were calculated. Breakeven costs were assumed to be equal to the present value of the savings generated (the fossil fuel and electricity costs saved) minus the present value of the annual costs associated with the SWECS. Assumptions were that (1) operations and maintenance costs (including property taxes and other miscellaneous costs) are 5 percent of fixed costs, and (2) the SWECS have a salvage value of zero at the end of the 20-year lifetime. These assumptions also are being used in other wind energy studies being prepared for USDA.

A payback analysis was performed, presenting annual outlays required for SWECS operation and resulting savings in conventional energy costs (assuming SWECS could be purchased at the breakeven cost level). Interest rates of 9 and 10 percent and 20 and 50 percent equity were assumed on 10-year loans. Payback--the point at which total accrued savings equaled or exceeded total outlays--occurred between the ninth and twelfth years. There was little sensitivity to the changes in interest rate or percent equity.

Breakeven costs then were compared with wind system costs projected at the 10,000th unit. The SWECS selected for comparison were those tested at Rocky Flats, all of which were rated at 8.9 meters per second (20 miles per hour), and for which comparable power curves were available. These SWECS ranged from one to 40 kW rated. Mean power output was calculated using the Rayleigh distribution and the power curves supplied by Rocky Flats. Mean outputs were calculated for three average wind speeds at 20 m: 4.4, 5.6, and 6.4 meters per second (100, 200, and 300 W/m^2, respectively). Projected SWECS costs at the 10,000th unit, obtained from Rocky Flats, were $3,000, $8,000, and $20,000 for 2-kW, 8-kW, and 40-kW machines, respectively. These costs did not include site preparation, installation, or any storage costs.

The comparisons of projected SWECS costs to breakeven costs indicated that SWECS are not economically viable for any system if operated over only a 6-week drying period. At best, the projected costs were about four times the calculated breakeven costs. Operation of most systems over 3 months in areas with wind power averaging 300 W/m^2 still would result in a ratio of projected to breakeven costs of greater than two. For alfalfa dehy facilities operating over 6 months, the projected costs (exclusive of site preparation, installation, and storage costs) with average available wind power of 300 W/m^2 (velocity of 6.4 meters per second at 20 m) did come close to breakeven.

Because electricity is more expensive than fossil fuels (on a heat- or kWh-equivalent basis), SWECS should be able to replace electricity more economically than fossil fuels. The assumption of higher escalation rates for fossil fuels than for electricity over time narrows these differentials, but electricity generated from oil or natural gas will continue to be significantly more expensive than the fuels themselves. Among the fuels, it currently would be most advantageous to replace the high-priced LPG or fuel oil, and least advantageous to replace natural gas. The ratio of projected SWECS cost to breakeven cost would fall if a heat pump were used in conjunction with the wind turbine, to replace or supplement both heating and cooling supplied by conventional energy sources.

Conclusions

Even if wind turbines are installed in regions of high wind power (over 300 W/m^2 at 20 m), the economics currently are not favorable if the systems are operated only for crop drying. Most crop dryers are operated for a maximum period of only 6 weeks to 2 months. The alfalfa dehy production season extends over several months, but individual facilities may not be operated for this entire period.

An additional problem is the availability of wind power during the drying seasons. However, if SWECS were to supply electricity for farm uses other than crop drying, their installation seems economically viable (given the assumptions enumerated above). SWECS should find the greatest use in low-temperature drying of grains and peanuts, where the dryers operate over relatively long periods of time and require substantial electricity but relatively little heat.

Because of the intermittent nature of the wind, unless low-cost storage systems can be used, wind energy is most likely to be used as a supplemental power source in crop drying. Further, it probably would not be economical to use wind energy alone in drying systems requiring short duration high temperatures; SWECS in these cases possibly could be used to achieve intermediate temperatures for longer periods.

Even if breakeven costs are achieved, payback periods are fairly long (9 to 12 years). The acceptability of this length of payback depends on the time horizons of farmers. While the payback most commonly sought by farmers is 5-7 years or less, there are farmers who are willing to accept longer payback periods.

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I. INTRODUCTION

Substantial amounts of the grain and other crops produced in the United States now are dried using artificial heat and ventilation, rather than being dried naturally in the field. In the case of grains, harvesting methods increasingly have involved direct combining and field shelling rather than field drying and threshing. About three-quarters of all corn for grain (over 5 billion bushels), a fifth of the soybeans (around 4 million bushels), all rice (134 million hundredweight), and most sorghum (980 million bushels) are dried artificially.[1] Smaller amounts of wheat, oats, barley, rye, and sunflowers also are dried in some areas. Nearly all peanuts (nearly 1.8 million kilograms in 1978) and tobacco (0.9 billion kilograms), and varying amounts of other nuts, fruits, and vegetables also are dried or cured artificially.

Artificial drying of grain has become increasingly popular because it offers several advantages to the grower. First, harvest losses are minimized. Harvesting losses of cereal grains in the United States average 5 percent of production, due to the shattering of grain that falls to the ground, wind and insect damage to the plants, improper operation of harvesting machinery, and poor growing conditions. A range of field losses of 2.3 percent to 22 percent has been reported for shelled corn. To obtain a yield with the maximum amount of dry matter, crops must be harvested at a moisture content well above that at which they can be stored successfully (e.g., 25 percent to 32 percent for shelled corn, 22 percent to 25 percent for rice, and 18 percent to 20 percent for wheat).[2] Second, field conditions may be better for harvesting early in the season--the ground may be drier and weeds may be fewer. Third, the ground can be prepared earlier for the next crop. Fourth, early harvesting and artificial drying allows for a better use of labor over time. Finally, grain that is dried to a moisture content suitable for storage for more than a few weeks can be sold several months after harvest at a higher price. An increase of 25 to 100 percent in grain prices after the harvest season is not uncommon.

Even if grain is to be marketed immediately, it must be dried to a moisture content substantially below that at which maximum harvest yields are achieved. Market prices are based on moisture contents of 15.5 percent for No. 2 (shelled) corn, 13 percent for No. 1 soybeans, 14 percent for No. 2 wheat, 15 percent for No. 3 grain sorghums, 14 percent for No. 2 oats, and 14.5 percent for barley.[3] If grain is to be stored for some time before use or marketing, moisture contents must be even lower (except for wet storage, which is used primarily for livestock feed). Table 1 indicates moisture contents required for several grains, at storage times of one and 5 years.

Some other crops, such as nuts, are dried artificially for some of the same reasons as are grains. All tobacco must be cured before sale, and most tobacco curing requires artificial heat although some is hung to dry naturally. Relatively little of the forage crop production now is dried artificially some experimentation was done in the 1950s, but artificial drying procedures generally proved too expensive for these crops. In some states alfalfa still is dehydrated for use in a high-protein livestock feed. In states such as California, fruits, particularly grapes and dates, sometimes are dried for final use.

Table 1. GRAIN MOISTURE CONTENT REQUIRED FOR SAFE STORAGE

Grain	Moisture Content Required for Storage (%)	
	1 Year	5 Years
Barley	13	11
Corn	13	10-11
Oats	14	11
Rice	12-14	10-12
Rye	13	11
Sorghum	12-13	10-11
Wheat	13-14	11-12

Source: Donald B. Brookes, Fred W. Bakker—Arkema, and Carl W. Hall, *Drying Cereal Grains* (Westport, Conn.: The AVI Publishing Company, Inc., 1974), p. 12.

Although artificial drying of crops is advantageous in many respects, it is a very energy-intensive procedure. In 1974 a total of about 77 million gallons of fuel oil, 664 million gallons of liquid petroleum gas (LPG; mostly propane), 27 billion cubic feet of natural gas, and 858 million kilowatt hours of electricity were consumed by crop-drying procedures (over 110,000 terajoules).[4] Corn requires the most energy for drying the entire crop, followed by tobacco, soybeans, rice and peanuts.

The energy requirements of crop drying on a state basis are indicated in table 2. Absolute amounts of fuels used undoubtedly have changed--and probably increased--since 1974, but the relative positions of the states probably are the same. The states of Illinois, Iowa, Nebraska, and North Carolina use by far more energy in crop drying than other states. Illinois, Iowa, and Nebraska are top corn-producing states; North Carolina produces corn and also is a big tobacco-growing state. Other midwestern and southeastern states use substantial amounts of energy for crop drying, as does California. Those states that use little or no energy for this purpose include primarily the New England states, as well as a few others that do not produce crops requiring drying. (Although this table shows no energy consumed in Delaware for crop drying, significant amounts of grains now are dried in that state.)

On a fuel basis, LPG and natural gas are the most commonly used energy sources in crop drying. Natural gas is used most frequently in some of the southeastern and midwestern states. Fuel oil is less commonly used, and is found primarily in the southeastern states.

The purpose of this study was to determine to what extent the energy used in crop drying can be supplied economically by small wind systems. Six major crops were selected for emphasis: corn, soybeans, rice, tobacco, peanuts, and forage (alfalfa dehydration). In section II, the equipment and procedures used in drying these crops are described, and energy requirements for individual drying facilities of various sizes and types are estimated. The location of crop-drying facilities is compared with wind patterns in section III, to provide information on what parts of the country have the capability to use wind energy in drying. Estimates of the number of drying facilities of different types are presented by state, and wind availability is analyzed by season. Section IV presents an economic analysis of the feasibility of wind power use, including calculations of breakeven costs for several crop-drying systems, estimates of energy output for some small wind systems, and comparisons of breakeven costs versus the projected costs of these wind systems. A payback period analysis is included. Summary and conclusions are presented in section V. Appendixes A and B present wind data and the methodology used in estimating numbers of grain-drying facilities, respectively; appendix C contains examples of the payback period analyses; small wind systems used for the analysis in section IV are listed in appendix D; and appendix E contains the Bibliography.

Measurements in this report - temperatures, energy units, weights, etc. - are given in metric units. For convenience, the commonly used U.S. equivalent units also are presented, in parentheses, in the text.

Table 2. CROP-DRYING ENERGY REQUIREMENTS BY STATE, 1974

State	Fuel Consumed: Fuel Oil (000 gals)	LPG (000 gals)	Natural Gas (mcf)	Electricity (m kWh)	Total Energy (TJ)
Alabama	420	2,126	64	4	362
Alaska	—	—		—	—
Arizona[a]	—	57	251	3	294
Arkansas	—	4,326	2,263	19	3,008
California	—	2,410	3,004	22	3,650
Colorado	—	2,059	666	6	964
Connecticut	—	1,075	—	—	108
Delaware[b]	—	—	—	—	—
Florida	1,684	5,148	40	7	832
Georgia	8,232	25,979	520	37	4,530
Hawaii	—	—	—	—	—
Idaho	—	—	483	6	557
Illinois	75	107,693	321	92	11,493
Indiana	21	54,638	145	46	5,807
Iowa	127	92,192	549	82	10,164
Kansas	—	16,603	2,462	47	4,559
Kentucky	1,345	7,640	236	6	1,249
Louisiana	—	3,034	1,301	12	1,877
Maine	—	—	—	—	—
Maryland	72	2,202	96	3	348
Massachusetts	—	—	—	—	—
Michigan	33	10,778	383	14	1,559
Minnesota	144	40,966	366	39	4,672
Mississippi	503	777	105	4	282
Missouri	182	20,899	450	26	2,716
Montana[a]	—	—	326	4	376
Nebraska	12	37,879	6,595	108	11,494
Nevada[a]	—	—	104	1	119
New Hampshire	—	—	—	—	—
New Jersey	—	—	—	—	—
New Mexico	—	42	133	2	157
New York	—	—	—	—	—
North Carolina	45,785	115,847	490	111	19,315
North Dakota	—	36	111	2	132
Ohio	2,638	22,232	1,114	35	3,977
Oklahoma	—	142	322	4	385
Oregon	—	—	231	3	267
Pennsylvania	143	4,073	435	9	942
Rhode Island	—	—	—	—	—
South Carolina	7,958	20,643	66	22	3,398
South Dakota	6	21,561	150	19	2,397
Tennessee	500	1,758	311	6	615
Texas	—	4,118	2,035	18	2,731
Utah	—	—	189	2	217
Vermont	—	—	—	—	—
Virginia	6,635	20,208	61	16	3,132
Washington	—	—	316	4	364
West Virginia	—	—	4	—	—
Wisconsin	46	15,286	410	17	2,053
Wyoming	—	—	—	—	—

[a]More recent data indicate considerable drying.
[b]No longer dry much grain

Source: U.S. Federal Energy Administration, *Energy and U.S. Agriculture: 1974 Data Base,* Vol. 1, pt. A, *U.S. Series of Energy Tables* (Springfield, Va.: National Technical Information Service, 1976).

Tables show metric measurements only. Exceptions are the units in which crops are measured and units of fossil fuels. Crops are discussed in terms of bushels, hundredweight, or tons (depending on the specific crop), since farmers deal with them in these units. Units of fossil fuels are listed in terms of cubic feet (natural gas) and gallons (LPG and fuel oil), since they are priced and sold on this basis.

II. EQUIPMENT, PROCEDURES, AND ENERGY REQUIREMENTS

A. Corn and Soybeans

Several different kinds of grain-drying equipment exist, particularly for on-farm drying. These systems and their energy requirements are described below. Most of the research on grain drying has involved corn; thus, the information presented below applies primarily to corn. Soybeans and other grains (other than rice) are dried in the same dryers, but drying parameters and hence energy requirements differ slightly from those of corn. While some of the same dryers are used for rice as for other grains, rice-drying procedures generally are a little different. Consequently, rice equipment and procedures are discussed separately.

On-farm systems may be classified in three general categories: batch, continuous flow, and in-storage layer. In bin batch drying, a 0.6 to 1.2 meter (m) (2- to 4-foot (ft) layer of grain is placed in a bin, dried, then cooled and removed. The usual practice is to harvest, dry and cool one batch each day in the drying bin, then move the grain to another storage bin; however, 2 or even 3 batches can be dried each day. It is possible to dry 20 or more batches per year in one batch facility, although 15 batches is about average. The number of bushels (bu) that can be dried depends on the size of bin, as illustrated in table 3.

Batch drying commonly is used for production of between 5,000 and 30,000 bushels per year. If stirring equipment is used, greater batch depths are permitted and convenience and capacity are increased. One or more vertical augers circulate around the bin, constantly bringing dry grain from the bottom and blending it with wetter grain on top. Batch drying with stirring equipment is appropriate for operations drying 10,000 to 50,000 bushels per year.

Air temperatures in batch drying range from about 49° to 66° C (120° to 150°F), or 43° C (110° F) for seed. Airflow rates range from 0.3 to 1.1 cubic meters per minute (cmm) (10 to 40 cubic feet per minute (cfm)) per bushel. Required kilowatts (kW) for the fan may be anywhere from 2.2 to 18.6 (3 to 25 horsepower (hp)), depending on bin size, the amount of corn being dried, and drying time.

Batch drying also may be achieved in portable batch dryers. A portable batch dryer consists primarily of a grain-holding compartment through which air is passed from a tractor or motor-powered fan. In the column type of dryer, a 30- to 61 centimeter (cm) (2- to 4-ft) column of grain is wrapped partially or entirely around an air chamber. Hot air forced into the plenum from a fan heater unit passes through the grain-filled column and evaporates the grain moisture. Airflow rates of from 0.9 to 2.3 cmm/bu (30 to 80 cfm/bu) are common, and air temperatures range from 82° to 93°C (180° to 200°F) for feed corn, 60°C (140°F) for grain for further processing, and 38° to 43°C (100° to 110°F) for seed. Illinois survey data indicates that the average drying temperature used in that state is 82°C (180°F). Burners generally have a capacity of about 4.2 to 6.3 gigajoules (GJ) (4 to 6

Table 3. NUMBER BUSHELS CORN DRIED IN DIFFERENT SIZE BINS

Bin Diameter (m)	(ft)	Maximum Bu Dried/yr
5.5	18	7,500
6.4	21	11,250
7.3	24	13,500
8.2	27	17,250
11.0	36	30,000
12.1	40	37,000

Source: Larry van Fossen, *Bin Drying Shelled Corn* (Ames, Iowa: Iowa State University, Cooperative Extension Service, 1967).

million Btus per hour (hr)). Drying capacities range from 70 to 750 bu/hr. (In Illinois, average rated capacity for 5 points moisture removal is 255 bu/hr. Average initial moisture content is 23 percent, while average final moisture content is 14.3 percent.) A typical batch dryer can remove about 10 percentage points of moisture from a 45-cm (18 inch) thick layer of grain in roughly 3 hours, operating at 60°C (140°F). From 15,000 to 25,000 bushels per year of production are needed to justify an on-farm portable batch dryer. The average number of bushels dried per year per portable batch facility in Illinois is 18,190.[5]

Continuous flow dryers are the most popular system for large grain producers and also for commercial grain buyers. They require about 30,000 bu/yr to be economical, and can handle over 50,000 bu/yr. In Illinois, the average amount of corn dried per continuous flow dryer is 31,650.[5] In continuous flow dryers, grain is added continually to the tops of drying columns and a thin layer of 20 to 30 cm (8 to 12 inches) passes through first a drying section and then a cooling section before being unloaded. Continuous flow drying eliminates grain-cooling time required in bin-drying systems, and avoids the necessity to stop drying to transfer grain to storage. Continuous loading and unloading is required.

The average drying rate for on-farm continuous flow dryers in Illinois is 370 bu/hr, with an average drying temperature of 82°C (179°F).[5] Temperatures may range up to 121°C (250°F), and fan requirements also are very high (75 to 125 cmm/m^2). Grain remains in the continuous flow dryer for only 2 to 3 hours.

Commercial dryers in the midwestern states range from 400 to 2,800 bu/hr average capacity. Average dryer capacities by storage capacity are shown in table 4 for six of these states. Most of these dryers are continuous flow. Average bushels of corn dried per facility in Illinois was estimated to be 695,000, but varied from 239,000 bu (for elevators with under 500,000 bu storage capacity) to 2,087,000 bu (for those with 1,500,000 or more bu storage capacity). However, small country elevators probably are undercounted so that the averages are overstated. Estimated average capacity for grain elevators in the country as a whole is about 476,000 bu (total off-farm capacity of about 6,993 billion bu, and total number of elevators estimated at about 14,680).[6]

Average number of dryers per elevator, for elevators equipped with drying facilities in the same six midwestern states, are shown in table 5. About 40 percent of all respondents (with dryers) in the ESCS survey from which tables 4 and 5 were drawn had only one dryer, about 40 percent had two dryers, 15 percent had three, and roughly 5 percent had four or more.

The third kind of drying system, in-storage or in-bin layer drying, involves the drying of a layer of grain 1.2 to 2.4 m (4 to 8 ft) deep with fairly low heat of 27° to 38°C (80° to 100°F). Once one layer is dried, another is added. In-storage drying is a slow process that works best where under 10,000 bushels are dried and stored. The

Table 4. AVERAGE DRYER CAPACITY BY STORAGE CAPACITY FOR 6 MIDWESTERN STATES

Storage Capacity (000 bu)	Average Dryer Capacity (bu/hr)					
	Illinois	Ohio	Minnesota	Iowa	Nebraska	Kansas
0- 100	600	464	469	1,014	400	530
101- 350	798	702	599	679	628	557
351- 500	997	1,053	810	1,050	563	723
501-1,000	1,157	1,405	1,208	1,187	970	754
1,001-2,500	1,627	1,545	1,394	1,447	983	856
2,501-5,000	2,635	—	—	2,664	2,214	1,019
Over 5,000	750	2,000	—	2,786	1,167	700

Source: U.S. Department of Agriculture, Economics, Statistics and Cooperatives Service. *Number and Physical Characteristics of Grain Elevators,* by L. D. Schnake and James L. Driscoll, 1978.

Table 5. AVERAGE NUMBER OF DRYERS PER ELEVATOR BY STORAGE CAPACITY AND STATE

Storage Capacity (000 bu)	Number						
	Illinois	Iowa	Minnesota	Ohio	Kansas	Nebraska	Total
0- 100	1.17	1.32	1.23	1.23	1.11	1.00	1.23
101- 350	1.44	1.50	1.74	1.58	1.23	1.53	1.52
351- 500	1.80	1.68	2.03	1.80	1.30	1.69	1.71
501-1,000	1.97	1.93	1.91	2.17	1.22	2.00	1.84
1,001-2,500	2.42	2.48	2.29	2.22	1.48	2.31	2.19
2,501-5,000	3.29	3.00	—	—	2.00	3.50	2.77
Over 5,000	2.00	3.50	—	1.00	2.00	3.00	2.43
Average	1.85	2.01	1.81	1.65	1.31	1.89	1.74

Source: U.S. Department of Agriculture, Economics, Statistics and Cooperatives Service, *Number and Physical Characteristics of Grain Elevators,* by L. D. Schnake and James L. Driscoll, 1978.

filling process requires up to 2 weeks with about 3 weeks required for the drying process for 25-percent moisture corn. The advantages of this type drying are less grain handling (once dried, the grain remains in the storage bin) and lower energy requirements due to low-temperature drying. On warm sunny days, naturally heated air alone may be circulated through the bin. However, bin drying must be completed by the beginning of November, before the onset of colder weather and higher humidity.

Approximate capacities, airflow rates, kilowatt, and heating requirements for different size bins are shown in table 6. Estimated storage capacities for several size bins with different depths of corn are presented in table 7. (Bins can be larger than the largest size indicated in these tables.) Table 8 gives average drying parameters and equipment information for the state of Illinois.

Energy Requirements

Energy for grain drying is primarily from LPG and natural gas for heating, and from electricity for fan operation. On farm operations most frequently use LPG. For instance, survey data from Illinois indicate that 96 percent of continuous flow and portable batch operations and 93 percent of bin-drying facilities use LPG, while the remaining few percent use natural gas. Survey data from Ohio show that 90 percent of the on-farm dryers in that state use LPG, and 7 percent use natural gas (the remaining 3 percent use only electricity, for low temperature drying, or did not respond). Off-farm commercial dryers tend more toward the use of natural gas. In Illinois, LPG is used in about 40 percent of commercial dryers, as opposed to natural gas in 47 percent. Around 7 percent use both these fuels and a further 3 percent operate with fuel oil.[5]

The amount of fuel required, both kWh of fan operation and heat, depends on several interrelated parameters: initial moisture content and desired final moisture content of the grain, ambient air conditions (temperature and humidity), drying temperature used, and drying time. In bin drying, the size of bin and depth of grain are factors. There is a tradeoff between kilowatt-hours (kWh) and heating energy requirements: an increase in the former can mean a reduction of the latter, and vice versa. In low-temperature drying, fans are operated over long periods of time rather than heating the grain to a high temperature. In general, batch and continuous flow dryers, which are high-temperature dryers, are more energy-intensive than drying in bin. (However, the drying of batches of grain in bin over a period of a day or less, with subsequent removal to another storage facility, should be considered high-temperature drying.)

Table 9 shows estimates of seasonal energy requirements for different sizes and types of grain-drying systems. These estimates necessarily hold some of the above variables constant, or assume an average value for them. Below, the fuel and electricity requirements for these systems, and the methodology used to obtain the figures in table 9, are described in detail.

Table 6. CAPACITIES AND EQUIPMENT REQUIREMENTS FOR GRAIN BINS

Bin Diameter (m)	Capacity[a] (bu)	Average Drying Capacity (bu/24 hrs)	Fan Air Flow @ 5.1 cm (cmm)	Approximate kW	Heater Rating (kJ)
4.3	1,970	—	107.7	1.49	68,575
5.5	3,250	145	178.0	2.61	110,775
6.4	4,450	195	242.3	3.73	147,700
7.3	5,800	300	316.5	5.60	195,175
8.2	7,350	325	400.6	8.95	247,925
9.2	9,050	580	494.5	11.19	305,950
11.0	13,025	710	712.0	14.92	422,000

[a]Six rings high, 4.9 m from drying floor to eave.

Source: Larry van Fossen, *Bin Drying Shelled Corn* (Ames, Iowa: Iowa State University, Cooperative Extension Service, 1967); John W. Glover and Robert W. Watkins, *In-Storage Grain Drying* (Raleigh, N.C.: North Carolina State University, Agricultural Extension Service, n.d.)

Table 7. STORAGE CAPACITIES FOR BINS BY CORN DEPTH (Bushels)

Bin Diameter (m)	Depth of Corn (m)			
	3.4	3.7	4.9	5.8
5.5	2,200	2,600	3,250	3,850
6.4	3,050	3,600	4,400	5,300
7.3	4,000	4,700	5,800	6,900
8.2	5,050	5,950	7,300	8,700
11.0	8,950	10,600	13,000	15,450

Source: Larry van Fossen, *Bin Drying Shelled Corn* (Ames, Iowa: Iowa State University, Cooperative Extension Service, 1967).

Table 8. BIN-DRYING PARAMETERS AND EQUIPMENT IN ILLINOIS

Type Bin	Average Bin Size (bu)	Average Bu/yr Dried	Average Initial Moisture	Average Final Moisture	Average Drying Time (days)	Average Drying (temp.)	Average Fan kW
Gas heated	6,860	8,970	22.6	14.4	12	38°C	6.7
Electric heated	7,510	7,370	21.4	15.0	25	—	7.8
No heat	5,800	5,400	18.9	15.0	33	--	2.8

Source: David W. Morrison and Gene C. Shove, *Survey of Grain Drying Practices in Illinois,* ASAE Paper No. 79-3026, 1979.

Table 9. SEASONAL GRAIN-DRYING ENERGY REQUIREMENTS

System	Energy Requirements			
	Size (bu/yr)	Natural Gas (000 cf)	LPG (gal)	Electricity (kWh)
Batch in bin	7,500	100	1,200	520
	37,500	510	5,900	2,600
Portable batch	10,000	120	1,400	300- 525
	25,000	310	3,500	4,500-8,750
Continuous flow	30,000	400	4,600	1,220
	50,000	660	7,600	2,030
	200,000	2,650	30,400	7,500
	1,000,000	13,270	152,100	40,000
	3,000,000	39,820	456,200	120,000
In-storage layer	2,000	20	200	640
	13,000	110	1,200	3,220
In-storage layer, electric heated only	2,000	—	—	1,340- 3,400[a]
	13,000	—	—	8,840-22,510[a]

[a]Lower figure refers to requirement for 0.56 °C (1 °F) temperature rise; higher figure refers to requirement for 2.78 °C (5 °F) temperature rise.

High-Temperature Batch Drying

A more complete picture of batch-in-bin drying energy requirements is presented in table 10. Required kWh to dry a batch of grain can range from about 30 for a 500-bushel batch dried in 8 hours to over 200 for a 2,500-bushel batch dried in 19 hours. Heat required per batch ranges from about 7.4 to 38.0 GJ (7 to 36 million Btus), which translates into about 80 to 400 gallons of LPG per batch, or 6,600 to nearly 35,000 cubic feet (cf) of natural gas. Between 13.7 and 16.9 megajoules (MJ) (13,000 and 16,000 Btus) per bushel are required in each case.

On a seasonal basis, assuming 15 to 25 days of dryer operation and one batch per day, a small bin dryer can require from 1,100 to 2,000 gallons of LPG (91,000 to 175,000 cf of natural gas). The largest bin would need 5,700 to 10,000 gallons LPG (510,000 to 872,000 cf of natural gas). The estimates presented in table 9 assume 15 batches dried per season, with batch sizes of 500 and 2,500 bu.

Estimates of the fuel requirements of portable batch dryers have been made for Illinois, where survey results indicate an average of 18,190 bu dried per season by this type dryer. The average number of moisture points removed is 8.7, using 1,540 kilojoules (kJ)/bu (1,460 Btu/bu) per point. Per season, then, the average LPG fuel requirement is about 2,600 gallons, while the amount of natural gas required would be 224,000 cf (244 GJ). Per day, assuming 15 to 25 days of dryer operation, between 100 and 170 gallons of LPG or 8,900 to 14,900 cf natural gas are necessary. Per batch, assuming that a batch requires 2 to 3 hours in the dryer and that the average dryer capacity is 225 bu/hr, the LPG fuel requirement is 70 to about 110 gallons, and the natural gas requirement about 6,300 to 9,400 cf. For smaller portable batch dryers of about 70 bu/hr capacity, the fuel requirement is around 20 to 30 gallons LPG (1,700 to 2,600 cf natural gas); for the larger sizes (750 bu/ hr), the requirement is between 210 and 310 gals LPG (18,480 to 27,700 cf of natural gas). The seasonal requirement for a very large facility (25,000 bu/yr) is close to 3,500 gallons of LPG or 308,000 cf natural gas.

Estimates of fan kWh were not given for portable batch dryers in the Illinois survey; however, based on required airflow of 0.9 to over 2.8 cmm/bu (30 to over 100 cfm/bu), required fan kW could range from 2.24 (3 hp) in the case of the small 70 bu/hr dryers up to 22.38 (two 15-hp fans) in the case of the large sizes. Per 2- to 3-hour batch, kWh requirements are between 4 and 7 for small batch dryers, and from 45 to nearly 70 for the large units. Seasonal requirements for smaller facilities, based on 5 batches a day and 15 operating days per season, would be between 300 and 525 kWh. For the large facilities, assuming more operating days (20 to 25), they would be 4,500 to 8,750 kWh.

High-Temperature Continuous Flow

Continuous flow dryers, like batch dryers, are high in energy requirements. Average kJ/bu/point of moisture removed in Illinois is 1,699 (1,610 Btus), with an average of 8.5 points removed. For an average size on-farm dryer of 370 bu/hr, LPG requirements are roughly 56

Table 10. DRYING TIME, FAN, AND HEAT REQUIREMENTS FOR BIN BATCH DRYING

Bin Diameter (m)	Batch Size (bu)	Estimated Drying Time (hrs)	Fan (kW)	kWh	Heater (kJ/hr)	kJ (m/batch)	LPG[a] (gals/batch)	Natural Gas[b] (000 cf/batch)
5.5	500	19		42.5	395,625	7.5	79	6.9
		13	2.24	29.1	553,875	7.2	76	6.6
		10		37.3	738,500	7.4	78	6.8
		8	3.73	29.8	949,500	7.6	80	7.0
6.4	750	19		70.9	553,875	10.6	111	9.7
		13	3.73	48.5	791,250	10.3	109	9.5
		10		56.0	1,055,000	10.6	111	9.7
		8	5.60	44.8	1,318,750	10.6	111	9.7
7.3	900	19		106.3	712,125	13.5	142	12.4
		13	5.60	72.7	1,002,250	13.1	138	12.0
		10		74.6	1,318,750	13.2	139	12.1
		8	7.46	60.0	1,846,250	14.8	156	13.6
8.2	1,150	19		106.3	844,000	16.0	169	14.7
		13	5.60	72.7	1,160,500	15.1	159	13.9
		10		74.6	1,582,000	15.8	167	14.6
		8	7.46	60.0	2,004,500	16.0	169	14.7
11.0	2,000	19		212.6	1,582,000	30.1	317	27.6
		13	11.19	145.5	2,215,500	28.8	303	26.5
		10		149.2	2,954,000	29.5	311	27.2
		8	14.92	119.4	3,798,000	30.4	320	27.9
12.2	2,500	19		212.6	1,978,000	37.6	396	34.5
		13	11.19	145.5	2,769,375	36.0	379	33.1
		10		186.5	3,692,500	36.9	389	34.0
		8	18.65	149.2	4,747,500	38.0	400	34.9

[a]Assumes 94,950 kJ (90,000 Btus) per gallon LPG.
[b]Assumes 1,088 kJ (1,031 Btus) per cubic foot natural gas.

Source: Larry van Fossen, *Bin Drying Shelled Corn* (Ames, Iowa: Iowa State University, Cooperative Extension Service, 1967. Converted to metric units from source.

gals/hr (4,911 cf/hr natural gas). Seasonal requirements for an average size facility (31,650 bu/yr) are 4,810 gals LPG (about 420,000 cf natural gas). For a larger facility drying 50,000 bu/yr, 7,900 gals LPG or 663,680 cf natural gas are required. Two 10-hp fans might be required for the average-size facility, which would mean 15 kW. To dry 31,650 bu at a rate of 370 bu/hr then requires about 1,280 kWh. To dry 50,000 bu would require over 2,000 kWh.

Commercial units, as indicated in table 4, have capacities of between 400 and 2,800 bu/hr. LPG requirements per hour for the smaller facilities are about 60 gallons (natural gas requirements -- 5,300 cf); for the larger facilities, about 430 gallons LPG, or 37,170 cf natural gas must be burned. Electrical requirements for the large commercial systems could be around 30 to 70 kW per hour of drying operation.

Energy requirements for five different sizes of continuous flow drying operations are presented in table 9. Fuel estimates were based on the average kJ/bu/point of moisture removed (1,699) and average number of points removed (8.5) obtained from the Illinois survey. Length of the operating season, for commercial establishments, can be as long as 70 to 90 days.

Low-Temperature Batch Drying

Fuel use in in-storage layer drying depends on weather the bin is heated by gas or electricity; the latter is used for very small amounts of heat only, up to 2.78°C (5°F). Grain may be dried using only the heat generated by the fan. The latter methods require more time to dry a given amount of grain (see table 8). Table 11 shows fuel and kWh requirements for different size gas-heated bins assuming an average operation of 12 days. In general, the capacity of the bin is the approximate amount dried. In Illinois, the average number of bushels dried per year in a gas-heated bin is roughly 8,970, requiring 880 gals LPG or 77,050 cf natural gas. Average fan hp is 9, which translates into about 1,930 kWh for 12 days.

Electrically dried grain has no fuel requirement, but kWh requirements are higher than for other drying methods. Table 12 shows electricity requirements for drying grain in different size bins both for a 0.56°C (1°F) temperature rise (0.174 kWh/ bu/point moisture removed, the average in Illinois for 3.9 points moisture removal), and for a 2.78° (5°F) temperature rise (0.270 kWh/bu/point for 6.4 points moisture removal).

Drying Grains with Less Energy

Because of the high energy requirements of grain-drying systems, other less energy-intensive methods have been developed. Low-temperature drying in bins, one method requiring less energy, is described above. Others are combination drying and dryeration.

Table 11. IN-STORAGE LAYER ENERGY REQUIREMENTS

Bin Diameter (m)	Capacity (bu)	kWh	LPG (gals)	NG (000 cf)
4.3	1,970	640	194	17.0
5.5	3,250	640	320	27.9
6.4	4,450	1,070	438	38.2
7.3	5,800	1,070	571	49.8
8.2	7,350	1,610	723	63.1
9.1	9,050	2,150	891	77.7
11.0	13,025	3,220	1,282	111.9

Table 12. ELECTRICITY REQUIREMENTS FOR ELECTRICALLY HEATED IN-BIN DRYING (kWh)

Bin Diameter (ft)	Capacity (bu)	0.174 kWh/bu/pt	0.270 kWh/bu/pt
14	1,970	1,340	3,400
18	3,250	2,210	5,620
21	4,450	3,020	7,690
24	5,800	3,940	10,020
27	7,350	4,990	12,700
30	9,050	6,140	15,640
36	13,025	8,840	22,510

In combination drying, grain is dried initially in a high temperature system using LPG or natural gas for heat energy. After the initial phase, it is discharged hot to the drying bin, slowly cooled, and dried with ambient air or low temperature air (heated 0.56° to 2.78°C). The high-temperature, high-speed phase can utilize a continuous flow or portable batch dryer, or a bin dryer using high temperatures. The process, like low temperature drying, takes considerable time. Combination drying may take 4 to 6 weeks or even longer, and may be halted in late fall and completed the following spring.

LPG and natural gas requirements for the high-speed drying are considerably reduced, as less moisture is removed in this phase of dryer operation. The exact amount of savings depends on initial moisture content and the moisture content at which the grain is discharged. Electrical energy requirements are increased above those of the typical high-speed drying operation, due to the low-temperature phase. However, total energy requirements are reduced. A further advantage is that drying capacity of the high-temperature system is increased, since less moisture is removed in the high-speed dryer.

University of Minnesota experiments performed in 1975, 1976, and 1977 indicated that LPG requirements for combination drying were from half to four-fifths those of conventional drying, depending on points of moisture removed and temperature (from 97° to 123°C, or (206° to 253°F) for the high temperature phase). Electricity requirements were about half those of conventional high-speed drying for the high-speed phase, and ranged from 0.10 to 0.13 kWh/bu per point moisture removed in the in-bin low-temperature stage. Between 29 and 58 days of fall fan operation were used, and in some of the experiments fans were operated again in the spring.[7]

The dryeration procedure involves rapid, high-temperature drying in batch or continuous flow dryers until a grain moisture level of 16 to 18 percent is achieved. Then the hot grain (air temperatures of 93°C and above are used) is transferred to a bin, and tempered for 8 to 12 hours. After tempering, the grain is cooled slowly, using only 0.01 cmm/bu (0.5 cfm/bu) for approximately 12 hours. The grain will release 2 to 3 percent moisture, as nearly all the contained heat is utilized for evaporation. Like combination drying, dryeration decreases energy requirements in high-speed drying, and increases capacity of the drying system.

Of the commercial elevators drying grain in Illinois, 14 percent use dryeration, with an additional 28 percent planning to install dryeration within the next 5 years. The percentage using combination drying is 35 percent, with an additional 35 percent planning to install this system within 5 years.[5]

B. Rice

Rice in some areas of the country is dried using the same drying facilities that are used for other grains, with most drying performed on the farm. In Texas and California, however, rice drying is almost entirely a commercial operation.

Commercial rice dryers are columnar continuous flow dryers, similar to those described in the preceding section. There are two basic types: the nonmixing, in which the rice descends between two parallel screens 10 cm (4 inches) or more apart; and the mixing dryers, which are of many designs. The most popular of the latter are the baffle dryer, which has horizontal lengths of sheet metal set about 15 cm (6 inches) apart, shaped to guide rice downward in a zigzag path; and the Louisiana State University dryer, a large bin in which layers of inverted trough-shaped air channels are installed. Again the rice flows downward in a zigzag path. Heated air is directed into the inlet layers, passed through the rice, and leaves via the outlet layers.

Since the rice kernel is sensitive to unequal moisture distribution, excess moisture cannot be removed too rapidy or the kernel will be cracked. Therefore, rice is dried in stages, with several passes through the dryer. High-moisture green rice should receive its first dryer pass within 24 hours after harvest. Partially dried rice is held in the drying-handling tanks to temper between passes, until the moisture equalizes throughout the individual kernels. The number of passes required depends on initial moisture content. Final moisture content is around 10 percent.

In California, deep-bed drying also is used, where the moisture is removed more slowly but continuously with lowtemperature air. Multipass and deep-bed drying sometimes are combined, by removing some moisture during two to four passes through the hot air dryer, then moving the partially dried rice into deep-bed flat-storage warehouses equipped with high capacity aeration fans.

The size of commercial rice drying facilities is quite large, with towers reaching up to about 75 feet in height and 17 feet in diameter. A tower with drying capacity of 1,200 bu/hr requires a 37.3 kW (50-hp) blower, and about 3.2 GJ (3 million Btus) per hour (for a 21^{o} to $54^{o}C$ temperature lift).

A larger facility, with capacity of 3,500 bu/hr, requires 111.9 kW (150 hp) for fans and 9.1 GJ (8.6 million Btus) per 8 hour for temperature lift.[8] These facilities are designed to burn natural gas, LPG, fuel oil (No. 2), or a combination of fuels. Rice facilities have an estimated receiving season of 40 to 60 days, although receipts during the peak 15 days of harvest can contain 60 percent of the season's total.

Table 13 shows the amount of natural gas, or LPG, and electricity required to dry one million and 5 million bushels of rice, respectively, based on the above data. One million bushels are assumed to be dried in a 1,200 bu/hr facility over a period of 34 days. In the 5-million-bu case, a 3,500 bu/hr capacity tower is assumed to be used, drying the rice over a period of about 60 days.

Table 13. SEASONAL RICE-DRYING ENERGY REQUIREMENTS

Amount Rice (bu/yr)	Energy Requirements		
	Natural Gas (000 cf)	LPG (gal)	Electricity (kWh)
1,000,000	2,460	28,200	31,080
5,000,000	11,970	137,100	159,900

C. Peanuts

The most common peanut-drying facility in both the eastern and western states is the trailer, although some peanuts are dried in metal bins and sheds. Average capacity of these trailers is about 80 hundredweight (cwt), or 4 tons; a typical trailer size is 7 by 14 feet. A drying operation generally consists of several trailers or bins, and some of the larger commercial facilities in the Southwest have a capacity of around 10,000 cwt, or 500 tons.

All of the peanuts artificially dried are dried in forced-air units. In addition, artificial heat is used in nearly all the drying facilities (a few units in the Southwest utilize forced air only). Air flow rates in the forced-air system are controlled by the fan used, curing depth of the peanuts, the number of trailers (bins) used, and/or the air gate adjustment where more than one bin or trailer is connected to the same plenum. The airflow should be at least 50 cmm/m^2 of a curing floor at a static pressure of 2.3 cm (0.9 inches) of water for a trailer (1.9 cm for a bin). This volume of air gives a minimum flow rate (10 cmm/cm) for a 1.5 m (5-ft) depth of peanuts with initial moisture content of 25 percent. Airflows greater than this minimum shorten the drying time or allow for increased depth of peanuts to be dried; however, the maximum practical airflow for a system is approximately 70 cmm/m^2 of curing floor at a static pressure of 3.2 cm (1.25 inches) water.

Required airflow rates increase as the initial moisture content of the peanuts increases. In the Southwest, initial moisture content generally is around 15 to 23 percent, but in Virginia, it ranges from 20 to 40 percent. For a given cmm/m^2 (or cfm/ft^2) of curing floor space, then, the depth of peanuts is varied according to initial moisture content. Table 14 indicates maximum curing depths at different airflow rates and initial moisture contents. For safe storage, the moisture content must be reduced to 8 to 10 percent. Although table 14 shows possible curing depths up to 2.4 m (8 ft), usually it is recommended that peanuts be dried at no greater than 1.5 m (5 ft).

The heater in a peanut-drying trailer or bin should be able to supply at least an 11°C (20°F) temperature rise. Frequently, no heat is used in the daytime during good weather, whereas an 8° to 11°C (15° to 20°F) temperature rise may be provided at night. The exact temperature rise required depends on the relative humidity; a general rule of thumb is that an 11°C temperature rise reduces the relative humidity to about one-half its original value.

Energy Requirements

Approximate energy requirements can be determined from required airflow rates, initial peanut moisture content, and climatic conditions. During the harvesting season in Virginia (October); the average temperature is around 18°C (65°F), and the curing temperature rise should average between 6.7° and 7.2°C (12° and 13°F). Assuming such a temperature increase, about 76 hours are required to dry peanuts

Table 14. MAXIMUM PEANUT-CURING DEPTHS BY AIRFLOW AND INITIAL MOISTURE CONTENT (M)

Airflow		Initial Moisture Content				
cmm/sq m	cmm/trailer	40%	35%	30%	25%	20%
70 @ 3.2 cm[a]	209.7	1.1	1.4	1.7	2.0	2.4
60 @ 2.5 cm	179.8	0.9	1.2	1.5	1.8	2.1
50 @ 1.9 cm	149.8	0.8	0.9	1.2	1.5	1.8

[a]Static pressure in cm water

Source: John W. Glover, *Mechanical Peanut Curing* (Raleigh, N.C.: North Carolina State University, Agricultural Extension Service, 1977). Converted to metric units from source.

of 30 percent moisture content in an average size trailer (80 cwt).[9] To dry 80 cwt of 30 percent-moisture peanuts to a final moisture content of 10 percent, 1,034 kilograms (kg.) (1,780 pounds) of moisture must be removed (10.1 kg per cwt). To remove a kilogram of moisture at recommended air flow, 6,499 to 7,195 kJ are required (35 to 40 percent fuel efficiency).[9] Thus, a total of 5.3 to 5.8 GJ (5.0 to 5.5 million Btus) are required to dry one trailer of peanuts. If LPG is used, as is typical of the Southeast and of on-farm drying in the Southwest, 70 to 80 gals are required. Electricity use for the 76-hour drying operation would be about 140 kWh, assuming a 2.5-hp fan. A typical on-farm drying operation in the Southeast might have six trailers, and dry 8 batches or 3,840 cwt annually (an average yield from 128 acres). Total fuel requirements in this case would be approximately 2,700 to 2,900 gals LPG and 6,700, kWh electricity.

A drying operation of the same size in the Southwest requires less energy because of the lower average initial moisture content of the peanuts and the lower relative humidity. Drying can be performed at lower temperatures without risking spoilage. To dry 80 cwt (one trailer) of 20 percent moisture content peanuts to a final moisture content of 10 percent, between 2.6 and 3.0 GJ (2.5 and 2.8 million Btus) are required, assuming the same fuel efficiency as above. LPG requirements thus are between 20 and 31 gallons per trailer. Less time is required to dry peanuts initially of 20 percent moisture content; based on 48 hours of fan operation, 90 kWh are required per trailer.

Table 15 lists approximate seasonal fuel and electricity requirements for peanut-drying facilities. Midpoint values of the ranges of fuel requirements are given, and it is assumed that energy requirements increase linearly with the amount of peanuts dried. Initial moisture contents of 30 and 20 percent are assumed, with drying to 10 percent.

D. Tobacco

Tobacco-curing facilities and techniques depend upon the type of tobacco. Leaves from flue-cured tobacco are picked individually as they ripen, and dried in conventional or bulk barns. In conventional barns the tobacco is hung on sticks, and artificial heat is supplied for drying. Fans may or may not be used to aid the natural convection currents in the barn. In bulk barns tobacco is packed in containers or racks, in roughly one-third the space used in conventional barns. Again, artificial heat is supplied, and artificial ventilation also is required in the bulk barns.

The conventional flue-curing procedure may be divided into four main phases: pre-yellowing, yellowing, color setting and leaf drying, and killing out. During the pre-yellowing phase, all surface moisture is removed from the leaves. Continuous fan operation is required for about 12 hours, and sometimes up to 48 hours. If the weather is very cool, heat may be supplied to raise the temperature to 32°C (90° F). Starting temperature for the yellowing phase is about 2.8° to 4.4°C (5° to 8°F) above the outside temperature, or around 32° to 38°C

Table 15. SEASONAL PEANUT-DRYING ENERGY REQUIREMENTS FOR PEANUTS OF DIFFERENT INITIAL MOISTURE CONTENT

	Energy Requirements					
	Initial MC = 20%			Initial MC = 30%		
Amount Dried (cwt/yr)	Natural Gas (000 cf)	LPG (gal)	Electricity (kWh)	Natural Gas (000 cf)	LPG (gal)	Electricity (kWh)
3,840	123	1,400	4,300	245	2,800	6,700
10,000	320	3,600	11,180	637	7,280	17,420
50,000	1,600	18,200	55,900	3,185	36,400	87,100
100,000	3,200	36,400	111,800	6,370	72,800	174,200
300,000	9,600	109,200	335,400	19,110	218,400	522,600

(90° to 100°F), with relative humidity of 80 to 90 percent. This temperature is maintained for 30 to 40 hours, then increased gradually to 46°C (115°F). By this time (after 40 to 70 hours), 20 to 30 percent of the moisture is gone from the leaves. During the color-setting/leaf-drying stage, the temperature is further increased to 66°C (150°F). The entire process up to this point requires from 60 to 95 hours. The killing-out phase requires are temperatures of 77° to 79°C (170° to 175°F) until the stems dried. Total time required for curing may be as much as 150 hours.

Bulk-curing units can dry tobacco slightly more quickly than conventional barns, using the same procedures as outlined above but with a fan operating throughout the cure. Required airflow rate is at least 40 cmm/m^2 of floor area (at 2.5 cm sp) for barns with 2-tier racks or boxes 1.2 m (4 ft) deep, 50 cmm/sq m (at 3.2 cm sp) for barns with 3-tier racks or boxes 1.5 m (5 ft) deep, and 60 cmm/sq m (at 4.45 cm sp) for barns with boxes 1.8 m (6 ft) deep. In terms of fan kW, a 23.2 m^2 (250-square-foot) bulk barn with 1.5-m-deep box containers requires a 3.73-kW (5-hp) fan assuming 50 percent fan efficiency. Required fan kW for different type barns (all 23.2 m^2) and two levels of fan efficiency are shown in table 16.

Energy Requirements

LPG generally is used in flue curing tobacco, although fuel oil is used in Virginia. Green tobacco is about 80 to 90 percent water. Dry tobacco should have 15 to 20 percent moisture content, so that 75 to 88 kg water must be evaporated from each 100 kg green tobacco. Studies indicate a requirement of 25,500 to 30,200 kJ to cure a kilogram of tobacco in a bulk barn (11,000 to 13,000 Btus to cure one pound), and 25 percent more fuel to cure the same amount in a conventional barn (however, electricity also is required in bulk barns). The variation in energy use is caused by things such as leaf position, maturity, and moisture content; density of tobacco in barn; weather conditions; insulation and air leakage; and temperature control.[10]

Assuming a 23.2 m^2 barn with 1.5-m-deep boxes (35.4 cm, or 1,250 cf), between 130 and 223 GJ (123 to 211 million Btus), or 1,370 to 2,340 gallons of LPG, are required to cure the entire barn. A 25 percent increase for the conventional barn is between 1,710 and 2,930 gallons LPG. Continuous operation of a 3.73-kW fan for the 4 to 6 days required means an electricity usage of between 360 and 540 kWh. Assuming an average of five cures per season, the seasonal energy requirements are about five times those indicated per barn for an individual cure.

Tobacco other than flue cured also frequently requires substantial energy for drying. In the case of fired tobacco, grown in Maryland, Kentucky, and Virginia, the whole plant is cured and hung in conventional barns. The leaves are stripped after drying. Wood still is used for heat in some barns, whereas others use LPG or fuel oil. Natural ventilation, through ducts, is most common. Burley tobacco, grown in Kentucky, Virginia, Ohio, Missouri and other midwestern states, is sometimes hung in conventional barns and dried naturally. In other

Table 16. REQUIRED FAN KILOWATTS FOR TOBACCO BARNS

	Fan kW at:	
Barn Type	50% Efficiency	60% Efficiency
2-tier racks	2.39	1.94
3-tier racks	3.66	3.06
1.2-m-deep boxes	2.39	1.94
1.5-m-deep boxes	3.66	3.06
1.8-m-deep boxes	6.12	5.15

Source: John W. Glover, *Air Handling in Bulk Tobacco Barns* (Raleigh, N.C.: North Carolina State University, Agricultural Extension Service, 1977). Converted from hp to kW.

cases, artificial heat is supplied. An estimate of the amount of supplemental heat used in a conventional burley barn is 211 MJ (200,000 Btus) per hour per acre.[11] Assuming that an average size barn holds 5 to 8 acres of tobacco, the fuel requirement for 130 hours of firing is between 1,400 and 2,300 gallons of LPG, similar to the requirement listed above for flue curing. Artificial ventilation is used occasionally.

All shade and broadleaf tobacco grown in Connecticut is fired, again for approximately 5 to 6 days, and thus requires the same amount of energy as described above. In Wisconsin, on the other hand, tobacco is most frequently dried naturally.

Table 17 shows fuel and electricity requirements on a seasonal basis in both bulk and conventional barns. Fuel oil requirements are presented as well as LPG requirements (157.9 MJ/gal were assumed for fuel oil).

E. Alfalfa Dehy

Alfalfa dehydrator, or dehy, plants dry alfalfa cut when it is at less than one-tenth bloom stage, and pelletize it into a high protein meal. The equipment used is referred to as a dehydrating drum. Green chopped alfalfa goes through the drum to be dried, usually making more than one pass. Current models of the multiple-cylinder drum provide 3-stage drying with proper temperature and velocity ideally suited to the changing moisture content of the product contained.

Temperatures are very high--up to 982°C (1800°F) at the drum entrance. In the intermediate and outer cylinders, the temperature is considerably reduced, allowing moisture removal without damage to the product. When the product leaves the dryer, its temperature is about 77°C (170°F) (the gas temperature is 93° to 121°C at the exit point).

In the 1960s most dehydrators had a rated capacity of one ton of meal per hour, and the average output per season was below 1,814 metric tons (mt) (2,000 tons) per unit. The drums more recently installed, however, have larger capacities. The dehy plant in Montana (only one still operates in that state) dehydrates 1.8 to 3.6 mt (2 to 4 tons) per hour of finished product (most plants operate with one drum but some have two or more). Output of 7.3 mt (8 tons) per hour may be possible in a triple-pass 3-m (10-ft) diameter drum.

Energy Requirements

Factors affecting energy consumption in dehy operations include combustion control, the initial moisture content of the material, throughput, the extent of recirculation, and the extent of heat recovery. The large motors required in a typical dehy plant total upwards of 373 kW (500 connected horsepower). The burners may use natural gas, fuel oil, and even coal or wood fuels, although natural gas most frequently is used. Some dryers are equipped with dual fuel oil and gas burners. About 12,000 cubic feet of natural gas are required to produce 0.9 mt (one ton) of dehy forage containing 10 percent water from

Table 17. SEASONAL TOBACCO-DRYING ENERGY REQUIREMENTS

Type Barn[a]	Energy Requirements		
	LPG (gal)	Fuel Oil (gal)	Electricity (kWh)
Bulk	1,370-2,340	820-1,410	360-540
Conventional[b]	1,460-2,930	1,030-1,760	360-540

[a]35.4 cubic meters; 1.5-meter-deep boxes in bulk barn.
[b]For burley tobacco, curing energy requirements are approximately the same, but ventilation is seldom used. Figures given are specific to flue cured and fired.

a wet product containing 80 percent water, assuming ambient air temperature of 16°C (60°F), drum outlet temperature of 138°C (280°F), entering product temperature of 10°C (50°F), and exiting product temperature of 79°C (175°F). The energy required is reduced if the water evaporation load is reduced; a reduction of 65 percent initial moisture content reduces the energy demand by half. A well-designed and well-operated system demands about 3,700 kJ per kg (1,600 Btus per pound) of water evaporated.

The Montana dehy plant consumes around 26 million cf natural gas per year, but is on a fuel quota system. Several dehy plants have been closing down in recent years because of the expense and lack of availability of fuel.

Table 18 shows approximate natural gas and electricity requirements for different levels of seasonal dehy production. Seasonal output per drum ranges from 1,088 to over 4,444 mt (1,200 to over 4,900 tons), with most drums producing 2,000 to 3,300 mt per year. Natural gas requirements are based on data given above. Electricity requirements assume 2.7 mt (3 tons)/ hr of finished product for an average-sized plant (one drum) producing 2,721 mt (3,000 tons) over the season, and requiring 373 kW. This plant would operate for 1,000 hours, requiring 373,000 kWh. Electricity use for other size plants were scaled to ihis estimate. The electricity estimates are very rough, as no good data were available.

F. Age Structure of Drying Equipment

The survey conducted in Illinois looked at the age structure of grain dryers in that state.[5] Of on-farm continuous flow dryers in Illinois, 47 percent are under 5 years old, 38 percent 5 to 10 years old, and 10 percent over 10 years old (5 percent are of unknown age). Of on-farm batch dryers, 33 percent are under 5 years old, 49 percent 5 to 10 years old, and 15 percent over 10 years old (3 percent of unknown age). Average bin age for in-bin dryers is between 5 and 8 years, and average fan age is 4 to 7 years. Electrically heated in-bin dryers have been the most recently installed. These age structures are likely to apply to on-farm grain dryers in other states as well, particularly in the Midwest. The trend in recent years has been toward installation of on-farm facilities and away from elevator drying, because of the cost and waiting time involved at elevators.

Little information is available on the age of other drying equipment, but off-farm drying facilities are likely to be of greater average age than the on-farm dryers. Some of these facilities--particularly for rice and alfalfa dehy--have been operating since the 1940s, and are being replaced with newer, higher capacity equipment. Tobacco barns and peanut trailers also may range from old to recently installed; conventional tobacco barns are likely to be older than the bulk barns used for flue curing.

Table 18. SEASONAL FORAGE DRYING ENERGY REQUIREMENTS

Production (tons/season)	Energy Requirements Natural Gas (000 cf)	Electricity (000 kWh)
1,000	12,000	125
2,000	24,000	249
3,000	36,000	373
4,000	48,000	497
5,000	60,000	622

G. Seasons of Operation

Operation of drying equipment is dependent upon the time of harvest, and consequently peaks in the fall for most crops. Corn is harvested from about the middle of September to the end of November or the middle of December in most states. In Texas harvesting begins earlier, around the middle of July. The peak harvesting times are around the middle of these intervals. Soybeans are harvested during the same time. Rice harvesting begins around the middle of July in Texas and lasts until early December; in California rice is harvested between the middle of August and the middle of November. Peanuts are harvested from July through December in Texas, but usually during October and November in other states. Tobacco is harvested from August to October.

Most crop drying thus begins sometime in September, and continues through December. In-bin drying with little or no heat, as noted previously, may have to be discontinued before December, as low outdoor temperatures may cause the grain to freeze. Commercial drying facilities frequently operate over a greater part of the year than do on-farm facilities--perhaps for 4 to 6 months.

Forage dehydration can operate over several months, since several cuttings of alfalfa can be taken per year. Dehy production occurs primarily between May and October, with a small amount produced in April and November. In California, production is year-round with a peak period from February to May.

III. CROP-DRYING FACILITIES AND WIND PATTERNS

A necessary condition for the use of wind as an energy source in crop drying is that wind power be sufficient in those states growing and drying large amounts of crops, during the crop-drying season. On the basis of table 2 and information obtained from agricultural experts in various states, several states were eliminated from consideration. These states are listed in table 19. Although table 2 indicates some energy consumption for crop drying in Arizona, Montana, Nevada, and Utah in 1974, individuals in those states have indicated that crop drying now is nearly nonexistent. Because these are arid states, drying is not as important as it is in the midwestern and eastern states. In some cases, drying facilities have ceased to operate because of increasing energy costs. Several alfalfa dehydration (dehy) plants in various parts of the country have gone out of business for this reason. In Montana, one dehy plant remains in operation, and it is on a fuel quota. About 10 facilities that dry field corn only are operating in Arizona. No information on other drying facilities could be obtained for these states.*

Additional states were eliminated based on the wind patterns presented in figure 1. Figure 1 illustrates the areas at which wind power averages (annually) at least 100 watts per square meter (W/m^2) at 10 meters, 20 meters, and 50 meters. The contour map was generated using annual average wind power data reported in J.W. Reed's Wind Power Climatology of the 12 United States: Supplement.[12] The adjusted values of annual wind power (using standard sea level air density) at 10-, 20-, and 50-m heights above ground were used. Of the total number of observing stations reported, those stations where no anemometer height estimates could be made were eliminated from the study, with 630 stations remaining.** The number of stations used from each state are given in appendix A. An annual average wind power density of 100 W/m^2 was chosen as the cutoff point below which wind power would be insufficient to power a turbine. This value refers to total power in the wind, and roughly corresponds to a wind speed of 4.4 meters per second, (m/8) or 10 miles per hour. In reading the map, it should be noted that all areas in which wind power is at least 100 W/m^2 at 10 m also will have winds averaging over 100 W/m^2 at 20 and 50 m. Similarly, those areas which have this degree of wind power at 20 m also will have it at 50 m.

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Information for these states was obtained via personal communication from Charles R. Farr, Extension Agent, Cooperative Extension Service, Phoenix, Arizona; Saco DeHy, Saco, Montana; and the Crop Reporting Services of Nevada and Utah.

**

These 630 stations are mostly at airports and thus are not necessarily representitive in terms of wind power availability.

Table 19. STATES WITH LITTLE OR NO ENERGY USE IN CROP DRYING

Alaska	Montana	Rhode Island
Arizona	Nevada	Utah
Hawaii	New Hampshire	Vermont
Maine	New Jersey	West Virginia
Massachusetts	New York	Wyoming

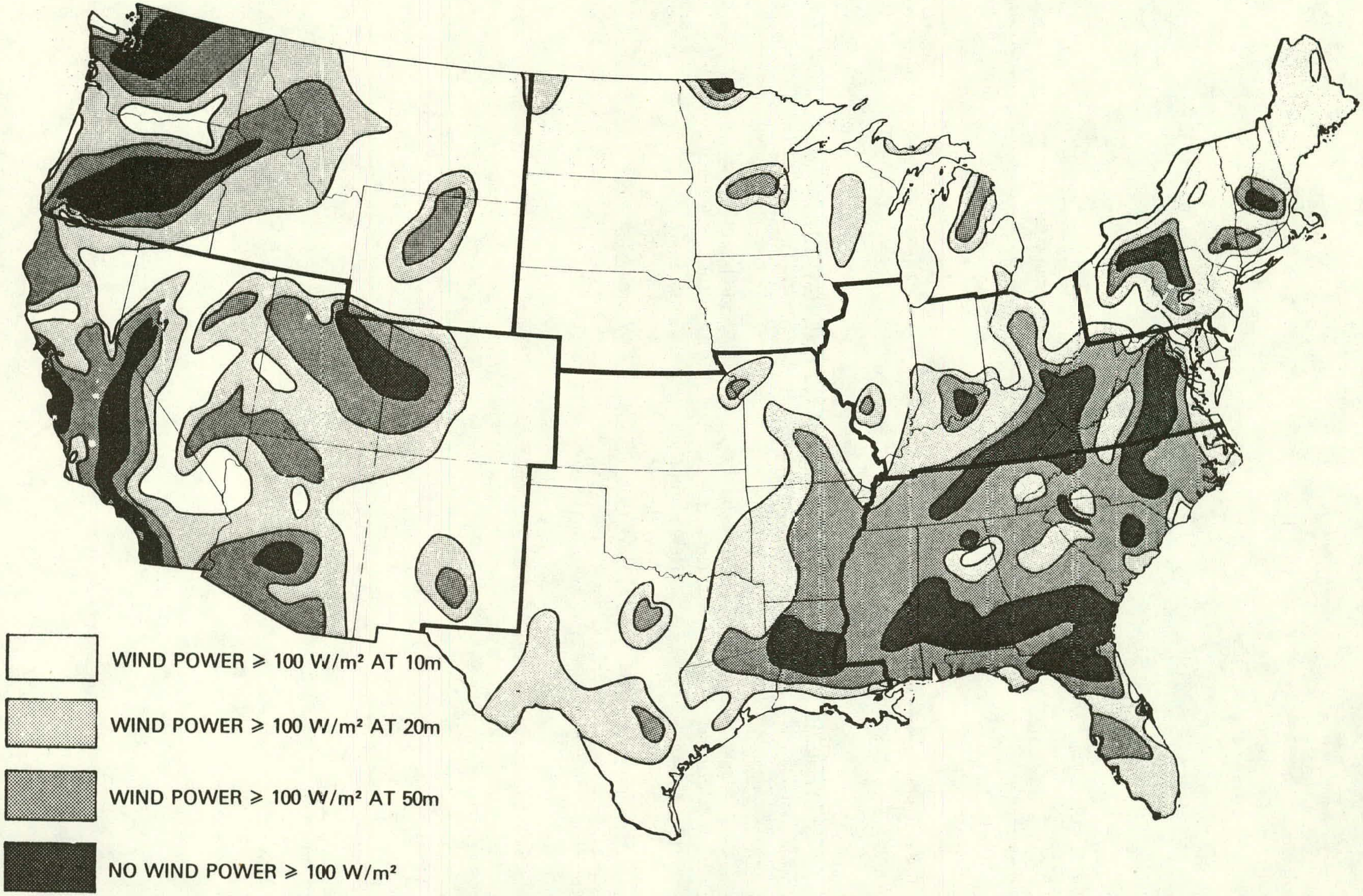


Figure 1. CONTOURED MEAN ANNUAL WIND POWER (W/m²) ESTIMATES OF THE UNITED STATES

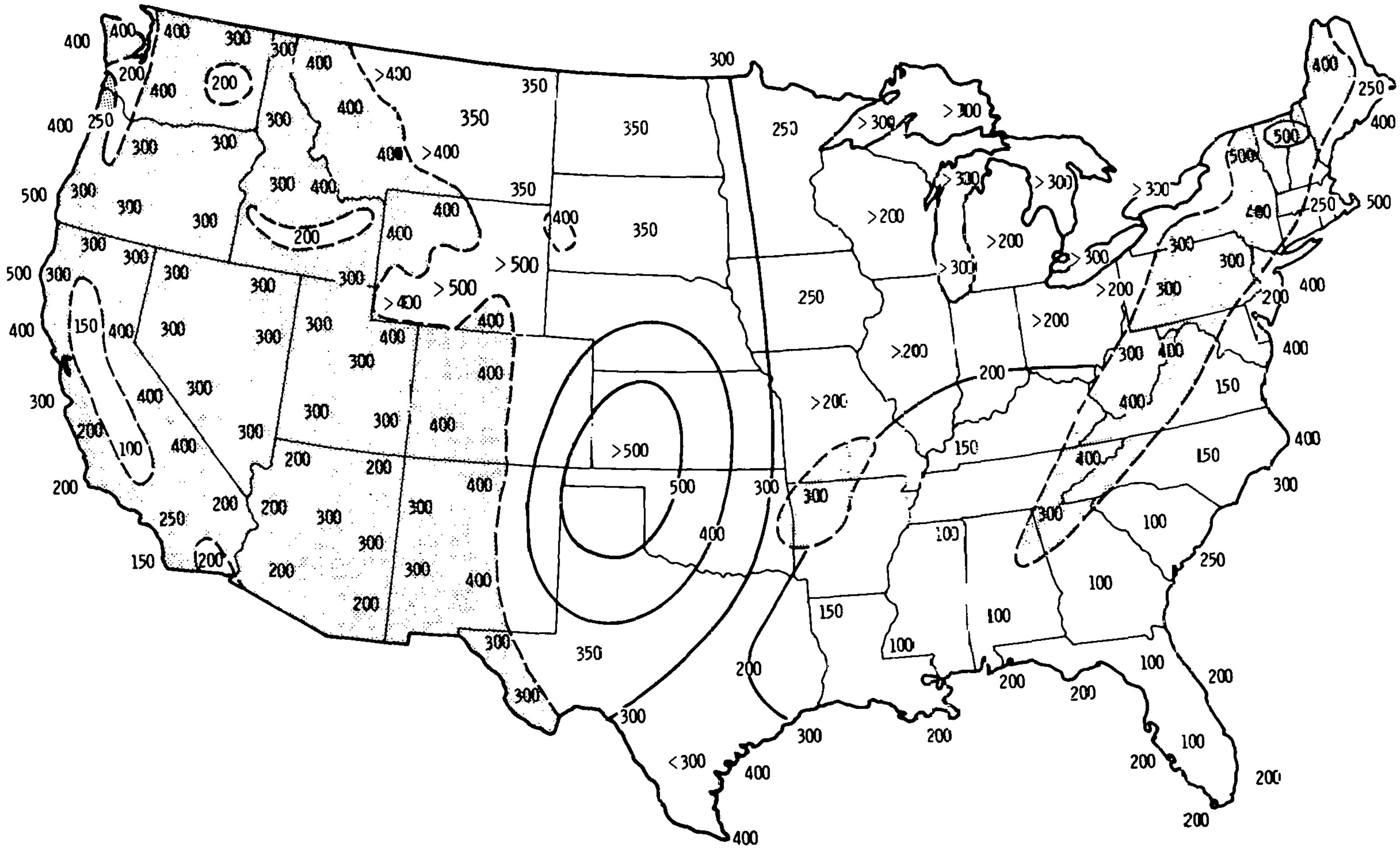
This wind energy classification map should be regarded as approximate; it was assumed in drawing the contour lines that physical wind phenomena were homogeneously transitional between data points. In other words, between a station with sufficient wind power at 10 m and above and one with sufficient wind power only at 50 m there was assumed to be a transitional zone with wind power of 100 W/m^2 at 20 m and above. Federally funded and university research that is currently proceeding will yield more detailed and accurate wind energy classification maps (e.g., the Battelle Northwest Study).

Figure 2 has been included to show specific average annual wind power estimates at 50 m. This map is more detailed than the preceding figure in that the latter show only zones where wind power is at least 100 W/m^2. However, figure 2 does not show wind powers at the lower heights. Ranges of average annual and peak average wind speeds measured below 20 meters are listed by state in appendix A.

Based on figure 1, table 20 presents three categories of states: those where wind is sufficient to support turbines at 10 meters over at least half the state (good); those with wind sufficient to support turbines at 10 meters over at least 25 percent of the state and at 20 meters over at least half the state (fair); and the remainder, for the most part consisting of those with wind sufficient only at 50 meters or not at all over at least half the state (poor). States in the third, or "poor" category were eliminated from the study. These states include the southeastern region plus the far Northwest (Oregon and Washington). Appendix A shows percentages of each state in the various wind regions.

The crops produced and artificially dried in the remaining states, of the six crops previously identified, are shown in table 21. The states that are large producers of corn, soybeans, and alfalfa dehy are good candidates for wind-powered drying systems. The two largest rice-producing states also remain in the sample, but few of the peanut- and tobacco- producing states remain. Most of the country's tobacco and many of the peanuts are grown in the Southeast, where the wind resource is limited.

California is a state that deserves special mention. Although wind power is adequate in much of the state, much of the crop production is in the large central valleys, where there is little wind. Consequently, relatively few of the drying facilities in California may be capable of utilizing wind energy.



Note: Over mountainous regions (shaded areas) the estimates are lower limits expected for exposed mountain tops and ridges.

Source: Dennis L. Elliott, "Synthesis of National Wind Energy Assessments," BNWL-2220 (Richland, WA: Battelle, Pacific Northwest Laboratories, July 1977).

Figure 2. MEAN ANNUAL WIND POWER (W/m²) ESTIMATED AT 50 m ABOVE EXPOSED AREAS

Table 20. STATE CLASSIFICATION BY WIND POWER

Good[a]	Fair[b]	Poor[c]
Colorado	California	Alabama
Delaware	Connecticut	Arkansas
Idaho	Maryland	Florida
Illinois	Ohio	Georgia
Indiana	Pennsylvania	Kentucky
Iowa		Louisiana
Kansas		Mississippi
Michigan		North Carolina
Minnesota		Oregon
Missouri		South Carolina
Nebraska		Tennessee
New Mexico		Virginia
North Dakota		Washington
Oklahoma		
South Dakota		
Texas		
Wisconsin		

[a]Wind power ≥100 W/m² at 10 meters over at least half the state.
[b]Wind power ≥100 W/m² at 10 meters over at least 25 percent of the state; at 10 or 20 meters over at least half the state.
[c]Wind power ≥100 W/m² only at 50 meters or not at all over at least half the state (over 45 percent of the state in Florida. However, Florida doesn't fit the second category since only 7 percent of its area has wind power ≥100 W/m² at 10 meters).

Table 21. CROPS GROWN AND DRIED IN STATES WITH AVAILABLE WIND POWER

State	Corn	Soybeans	Rice	Tobacco	Peanuts	Forage[a]
California	•		•			•
Colorado	•					•
Connecticut				•		o
Delaware	•	•				o
Idaho	o					•
Illinois	•	•				•
Indiana	•	•		•		•
Iowa	•	•				•
Kansas	•	•				•
Maryland	•	•		•		•
Michigan	•	•				•
Minnesota	•	•				•
Missouri	•	•	•			•
Nebraska	•	•				•
New Mexico	•				•	•
North Dakota	o	o				•
Ohio	•	•		•		•
Oklahoma	•	•			•	•
Pennsylvania	•	•		•		•
South Dakota	•	•				•
Texas	•	•	•		•	•
Wisconsin	•	•		•		•

[a]Alfalfa dehy

Key: o Grown but not dried or dehydrated
• Grown and dried or dehydrated

A. Number and Location of Drying Facilities

Grains may be dried either on the farm or in off-farm commercial facilities. In most midwestern states, a little over half the corn dried artificially is dried on the farm. In the eastern states relatively more grain appears to be dried in commercial facilities.* Soybeans are dried in the same facilities that dry corn, as is rice in Missouri. Rice in Texas and California is dried mainly in commercial facilities. Table 22 gives estimates of the number of on-farm and commercial grain drying facilities of various types in the states of interest. The methodology used to obtain these estimates is described in appendix B.

As table 21 indicates, only three states growing peanuts remain in the sample for this study. All three states (New Mexico, Oklahoma, Texas) are in the Southwest, where peanuts are dried primarily in commercial facilities. It has been estimated that 75 to 100 commercial drying facilities exist throughout these states.

Table 23 shows estimates of the number of conventional tobacco-curing barns in seven states (since bulk barns are used primarily for flue curing and states that flue-cure tobacco do not have much wind, bulk barn estimates are not presented). These estimates were derived based on the assumption that an average barn holds 5 to 8 acres of tobacco, and that five cures are performed per season. The estimates may be too small for stages where an appreciable amount of tobacco is dried without artificial heat or ventilation, since fewer cures probably then could be performed. Wisconsin is a state where much of the tobacco is dried naturally.

The greatest concentration of dehy plants is in the Platte River Valley of Nebraska and the Kansas River Valley of Kansas, but they are also located in several other states. The number of dehy drums currently producing in areas with wind availability, by region, are shown in table 24. Most dehy plants operate one drum, but a few operate more, so the number of plants is slightly lower than the number of drums shown. The number of drums reporting production in 1978 also is shown. A comparison of the 1978 and 1979 figures indicates either that several plants have closed down, or that several old small drums have been replaced with fewer large ones. Only one plant remains in Montana, and individuals in the states of Utah, Nevada, and Arizona have reported that no dehy plants are operating there now.

Figures 3 through 8 show the wind patterns presented in figure 1 on a regional scale also the numbers of crop-drying facilities in the relevant states are listed, to facilitate a comparison of crop-drying locations with available wind power. The best match of wind power with drying facilities is in the midwestern states

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Based on Corn Harvesting and Handling Reports from Illinois, Indiana, Iowa, Michigan, and Wisconsin; and the U.S. Department of Agriculture's most recent grain storage capacity survey.[13]

Table 22. NUMBERS OF ON-FARM AND COMMERCIAL GRAIN-DRYING FACILITIES, BY TYPE AND STATE[a]

State	Number Drying Facilities				Total
	On-Farm				
	Continuous Flow	Portable Batch	Bin[b]	Commercial	
MIDWEST					
Illinois	4,900	3,550	60,750	1,500	70,700
Indiana	4,700	6,100	17,400	500	28,700
Iowa	7,300	6,800	44,800	1,200	60,100
Kansas	800	800	5,200	1,100	7,900
Michigan	1,500	2,700	2,900	100	7,200
Minnesota	3,700	3,500	22,800	600	30,600
Missouri	2,100	1,800	18,400	400	22,700
Nebraska	4,000	3,800	24,900	800	33,500
Ohio[c]	1,100	—	8,800	400	10,400
South Dakota	1,200	1,200	7,700	100	10,200
Wisconsin	1,600	2,100	3,000	200	6,900
EAST					
Delaware		200		<100	<300
Maryland		1,200		100	1,500
Pennsylvania		4,600		<100	<4,700
WEST					
California[d]		400		300	700
Colorado		2,000		100	2,100
Idaho		<100		100	<200
SOUTHWEST					
New Mexico		200		<100	<300
Oklahoma		100		200	300
Texas[d]		1,700		1,000	2,700

[a]See appendix B for the methodology used in constructing this table. Numbers are rounded to the nearest hundred, except for Illinois.
[b]Includes batch-in-bin and in-storage-layer.
[c]1974 total estimate, from Ohio Grain, Feed and Fertilizer Assn., Inc.: 9300.
[d]Commercial drying facilities include rice facilities.

Table 23. TOBACCO ACREAGE AND NUMBER OF BARNS, BY STATE

State	Acreage (1977-78)	# Barns
Connecticut	3,740	95-150
Indiana	6,900	170-275
Maryland	23,000	575-920
Missouri	2,400	60- 95
Ohio	8,500	210-340
Pennsylvania	13,500	340-540
Wisconsin	12,100	300-485

Table 24. ALFALFA DEHY FACILITIES BY REGION

States	Number of Drums		
	1979		1978
	Owned	Reporting	Reporting
Nebraska	122	121	124
Kansas	60	57	60
Maryland Pennsylvania Ohio Michigan	45	45	51
Iowa Minnesota Wisconsin North Dakota South Dakota	35	34	38
Colorado Utah Montana Idaho	30	30	36
Illinois Missouri Indiana Kentucky	15	15	20
California	11	11	21
Texas Oklahoma New Mexico	6	6	13
Nevada Arizona Washington Oregon	3	3	3
Total	327	322	366

Source: American Dehydrators Association. Some states included in the Association's grouping were eliminated from this study based on data supplied by Crop Reporting Services in those states (e.g., Nevada, Arizona, Utah). Others were eliminated because of poor winds (Kentucky, Washington, Oregon).

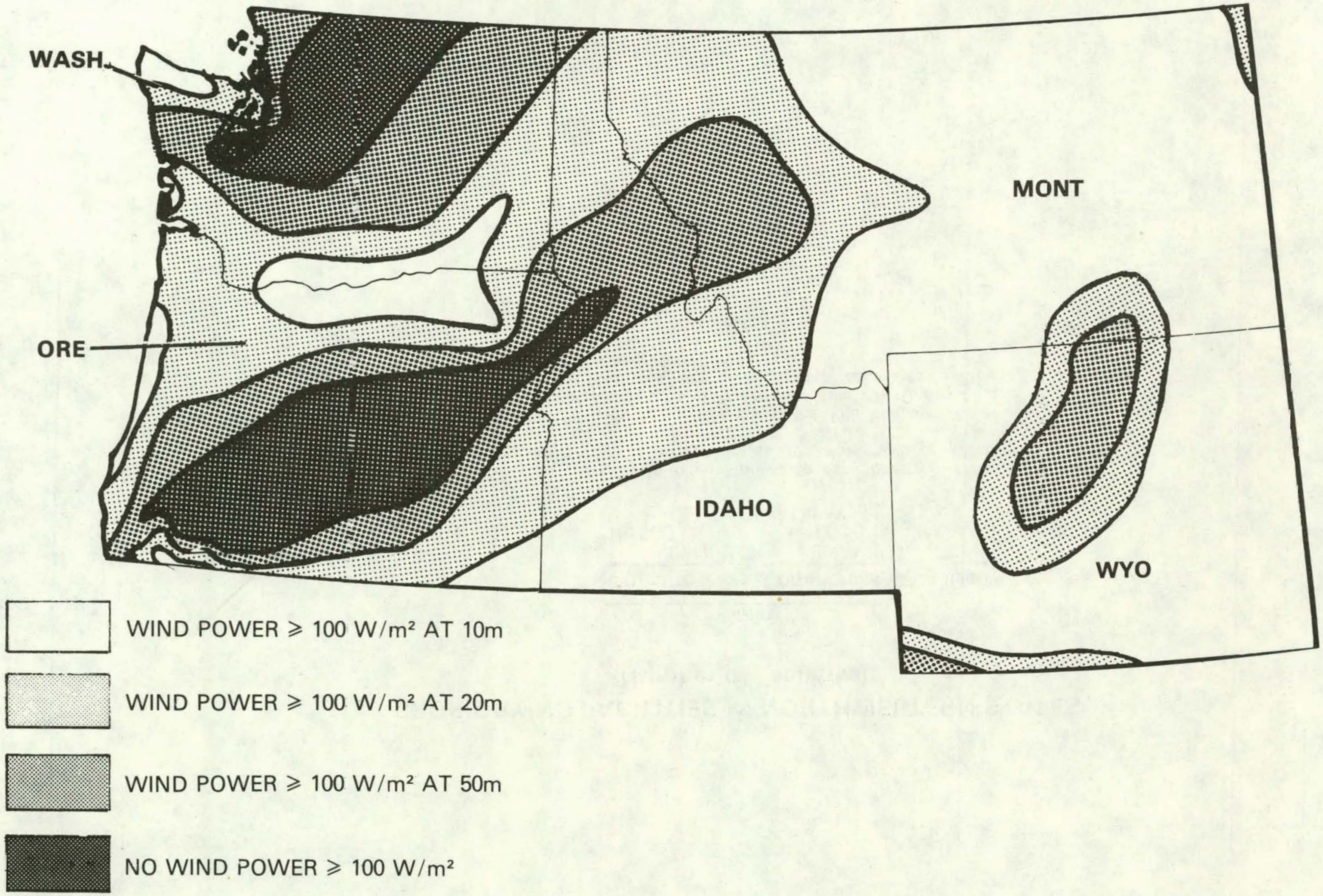


Figure 3. CONTOURED MEAN ANNUAL WIND POWER (W/m²) ESTIMATES OF THE NORTHWEST REGION

CROP-DRYING FACILITIES IN NORTHWESTERN STATES[a]
(Number of Facilities)

	Grain		
	On-Farm	Commercial	Dehy[b]
Idaho	<100	100	<29

[a]No crop drying in Wyoming; only one dehy facility in Montana. Other states excluded due to relatively poor winds (see table 16).

[b]Total of 30 dehy drums operate in the four states of Colorado, Utah, Montana, and Idaho (see table 20). One only is operating in Montana, and none in Utah, according to Crop Reporting Service personnel in those states.

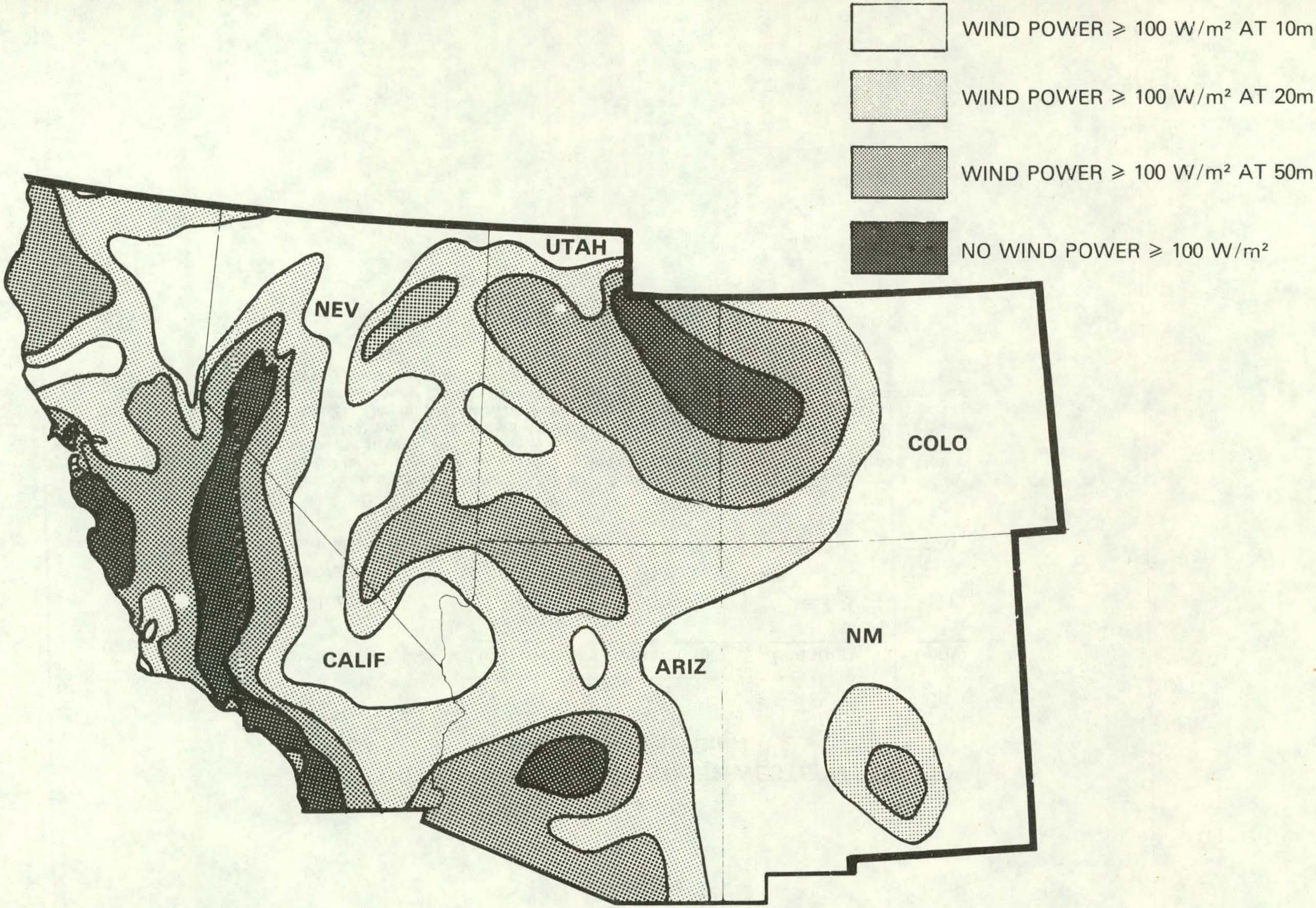


Figure 4. CONTOURED MEAN ANNUAL WIND POWER (W/m²) ESTIMATES OF THE SOUTHWEST REGION

CROP-DRYING FACILITIES IN SOUTHWESTERN STATES[a]
(Number of Facilities)

	Grain			
	On-farm	Commercial	Peanuts[b]	Dehy[c]
California	400	300	—	11
Colorado	2,000	100	—	<29
New Mexico	200	<100	<100	< 6

[a]Minimal crop drying in Nevada, Utah, and Arizona.
[b]75-100 facilities in the three states of Texas, Oklahoma, and New Mexico combined. Most of those are in Texas and Oklahoma.
[c]Total of 30 dehy drums operate in the four states of Colorado, Utah, Montana, and Idaho (see table 20). One only is operating in Montana and none in Utah, according to Crop Reporting Service personnel in those states. A total of 6 drums are operating in Texas, Oklahoma, and New Mexico (see table 20).

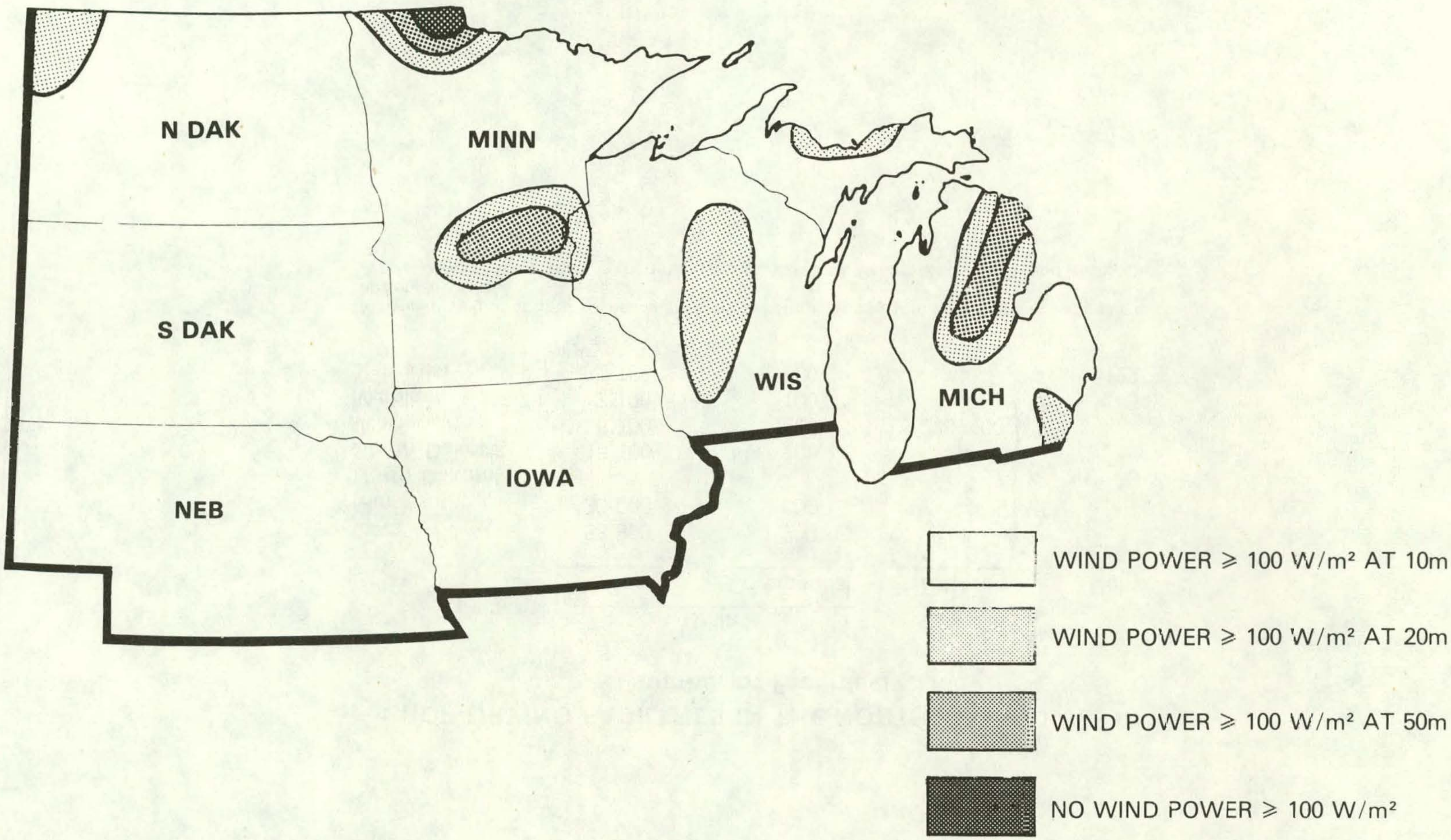


Figure 5. CONTOURED MEAN ANNUAL WIND POWER (W/m²) ESTIMATES OF THE NORTHERN MIDWEST

CROP-DRYING FACILITIES IN THE NORTHERN MIDWEST
(Number of Facilities)

	Grain			
	On-farm	Commercial	Tobacco	Dehy[b]
Iowa	58,900	1,200	—	
Minnesota	30,000	600	—	
North Dakota[a]	—	—	—	35
South Dakota	10,100	100	—	
Wisconsin	6,700	200	240-400	
Michigan	7,100	100	—	<45
Nebraska	32,700	800	—	122

[a]Minimal drying of corn or soybeans in North Dakota, although some other grains such as sunflowers are dried.

[b]A total of 45 drums operate in the four states of Maryland, Pennsylvania, Ohio, and Michigan.

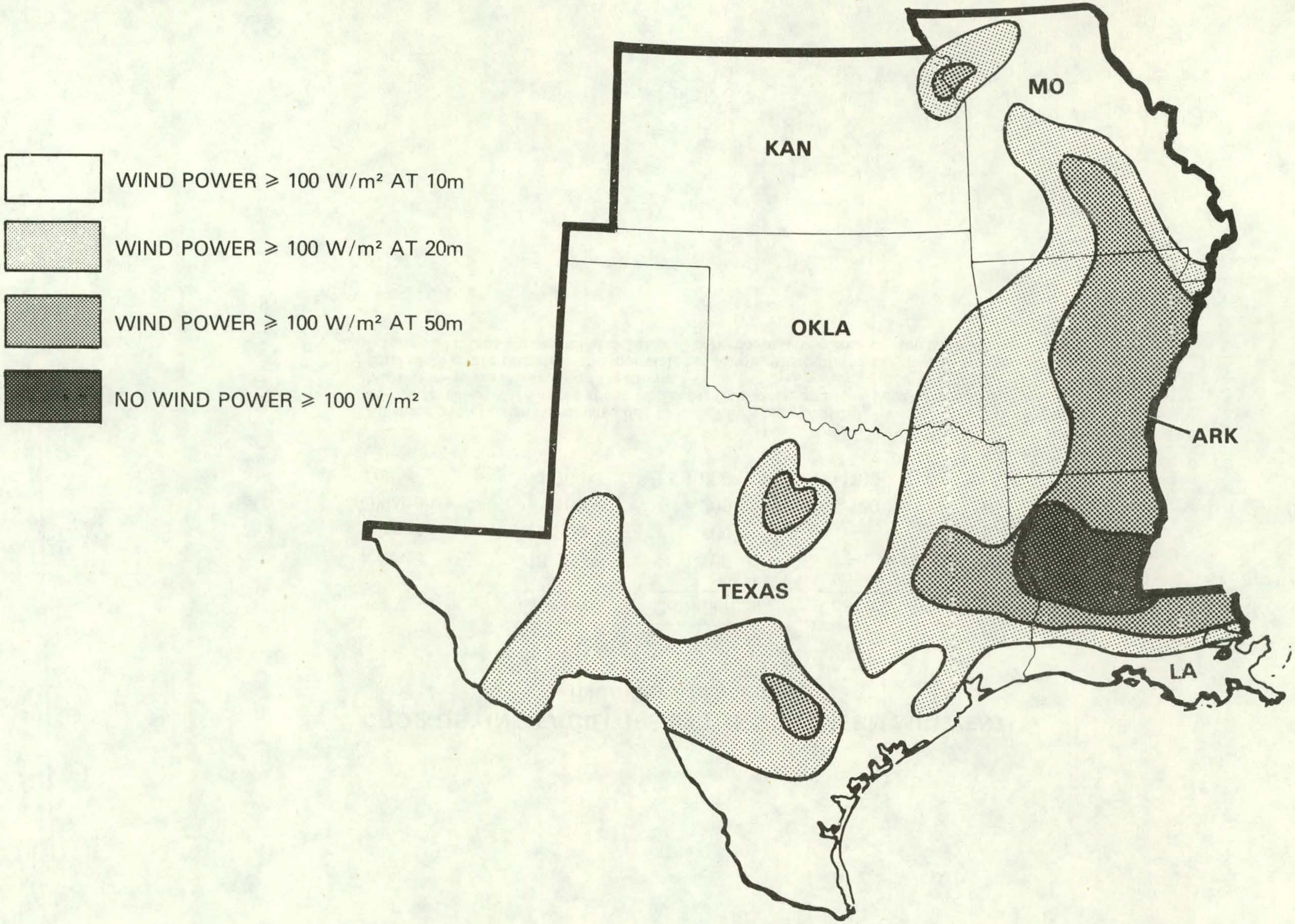


Figure 6. CONTOURED MEAN ANNUAL WIND POWER (W/m²) ESTIMATES OF THE SOUTHERN MIDWEST

CROP-DRYING FACILITIES IN THE SOUTHERN MIDWEST[a]
(Number of Facilities)

	Grain			
	On-farm	Commercial	Peanuts[b]	Dehy[c]
Kansas	6,800	1,100	–	60
Missouri	22,300	400	–	<15
Oklahoma	100	200	<100	< 6
Texas	1,700	1,000	<100	< 6

[a]Arkansas and Louisiana eliminated due to poor winds (see table 16).

[b]75-100 facilities in the three states of Texas, Oklahoma, and New Mexico combined. Most of these are in Texas and Oklahoma.

[c]Total of 15 drums operate in the four states of Illinois, Missouri, Indiana, and Kentucky. A total of 6 drums are operating in Texas, Oklahoma, and New Mexico (see table 20).

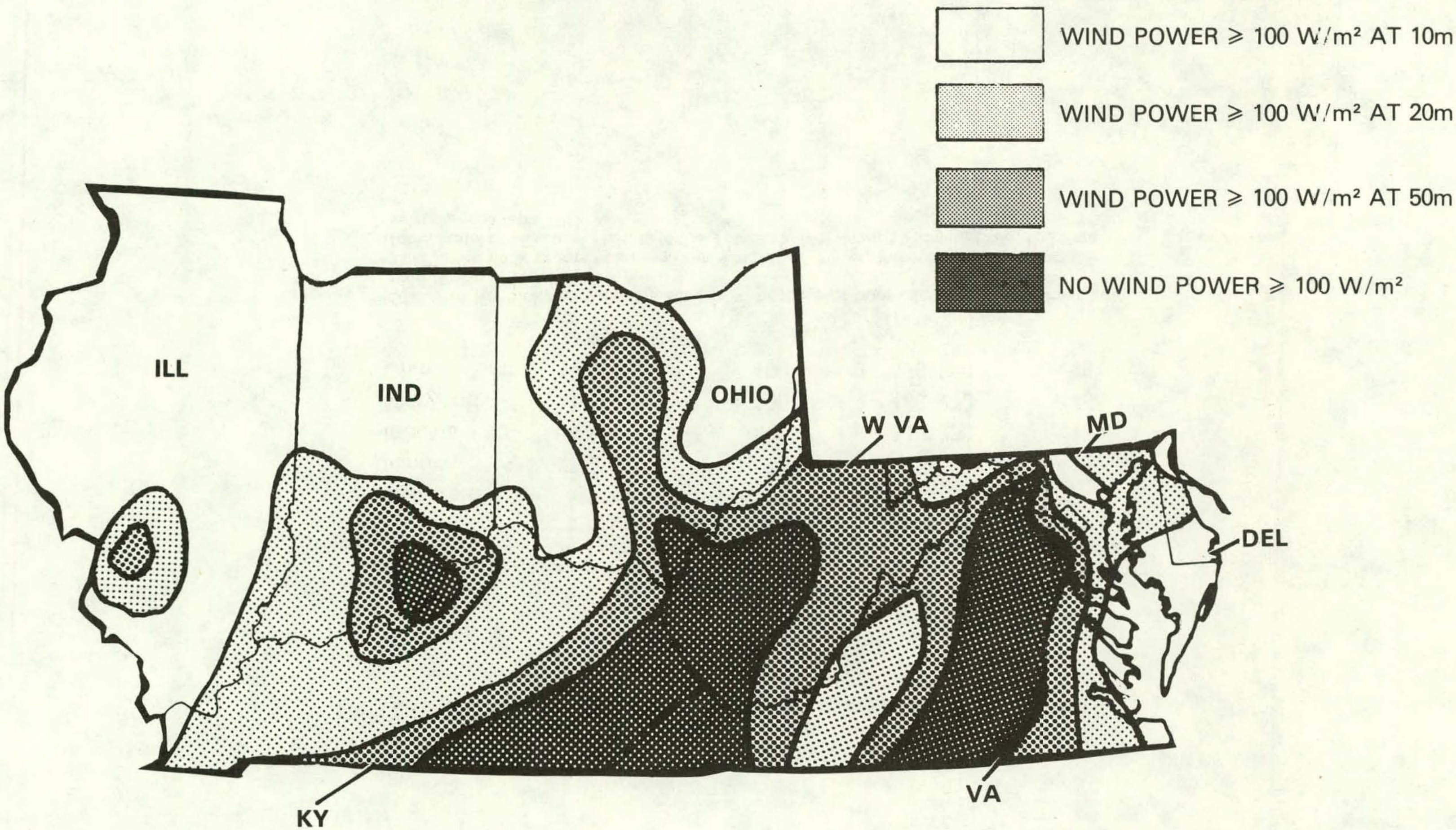


Figure 7. CONTOURED MEAN ANNUAL WIND POWER (W/m^2) ESTIMATES OF THE EASTERN MIDWEST AND MIDDLE ATLANTIC

CROP-DRYING FACILITIES IN THE EASTERN MIDWEST AND MIDDILE ATLANTIC STATES[a]
(Number of Facilities)

	Grain			
	On-farm	Commercial	Tobacco	Dehy[b]
Delaware	200	<100	–	–
Illinois	69,200	1,500	–	<15
Indiana	58,900	500	140-230	<15
Maryland	1,200	100	460-770	<45
Ohio	10,000	400	170-280	<45

[a]States of Kentucky and Virginia eliminated because of poor wind availability; minimal crop drying in West Virginia.
[b]Total of 15 dehy drums operate in the 4 states of Illinois, Indiana, Missouri, and Kentucky; total of 45 drums operate in the 4 states of Maryland, Michigan, Ohio, and Pennsylvania (see table 20).

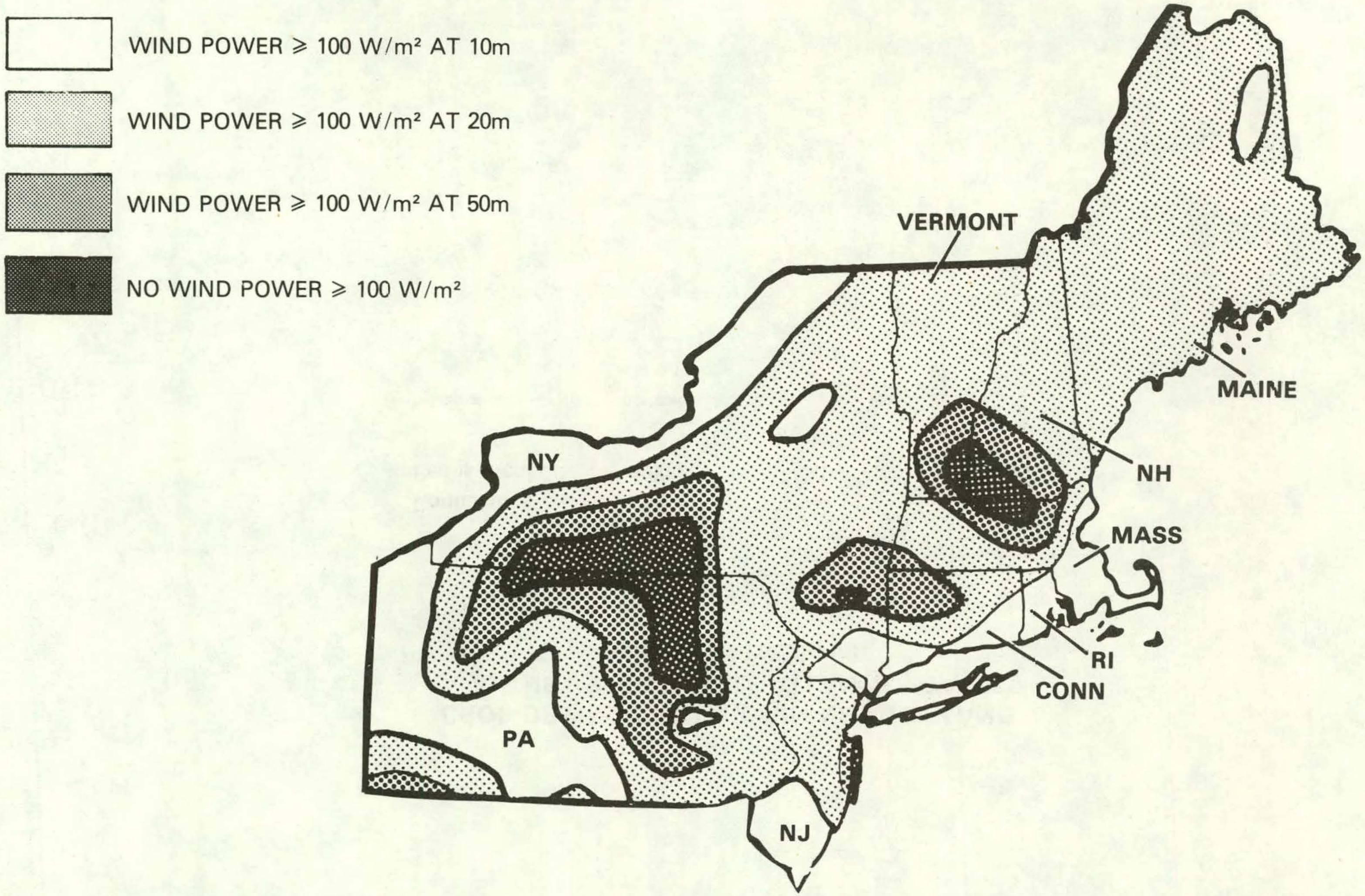


Figure 8. CONTOURED MEAN ANNUAL WIND POWER (W/m²) ESTIMATES OF THE NEW ENGLAND AND UPPER MIDDLE ATLANTIC

CROP-DRYING FACILITIES IN NEW ENGLAND AND THE UPPER MIDDLE ATLANTIC STATES[a]
(Number of Facilities)

	Grain		
	On-farm	Commercial	Tobacco
Connecticut	—	—	75-125
Pennsylvania	4,600	<100	270-450

[a]Minimal crop drying in other states.

figures 5, 6, and 7). These states have large numbers of grain-drying facilities (for corn and soybeans and, in Texas, rice) and several hundred tobacco barns. Several dehy facilities also operate in the Midwest. Although the western states (except for Oregon, Washington, and large parts of California) have good winds, there are fewer drying facilities located there. These states are quite dry, and the moisture content of grain at harvesting is relatively low. However, several dehy plants operate in these states. Alaska, Hawaii, and several of the southeastern states are not represented in these figures; no crop drying occurs in Alaska or Hawaii, and winds are relatively poor in the Southeast.

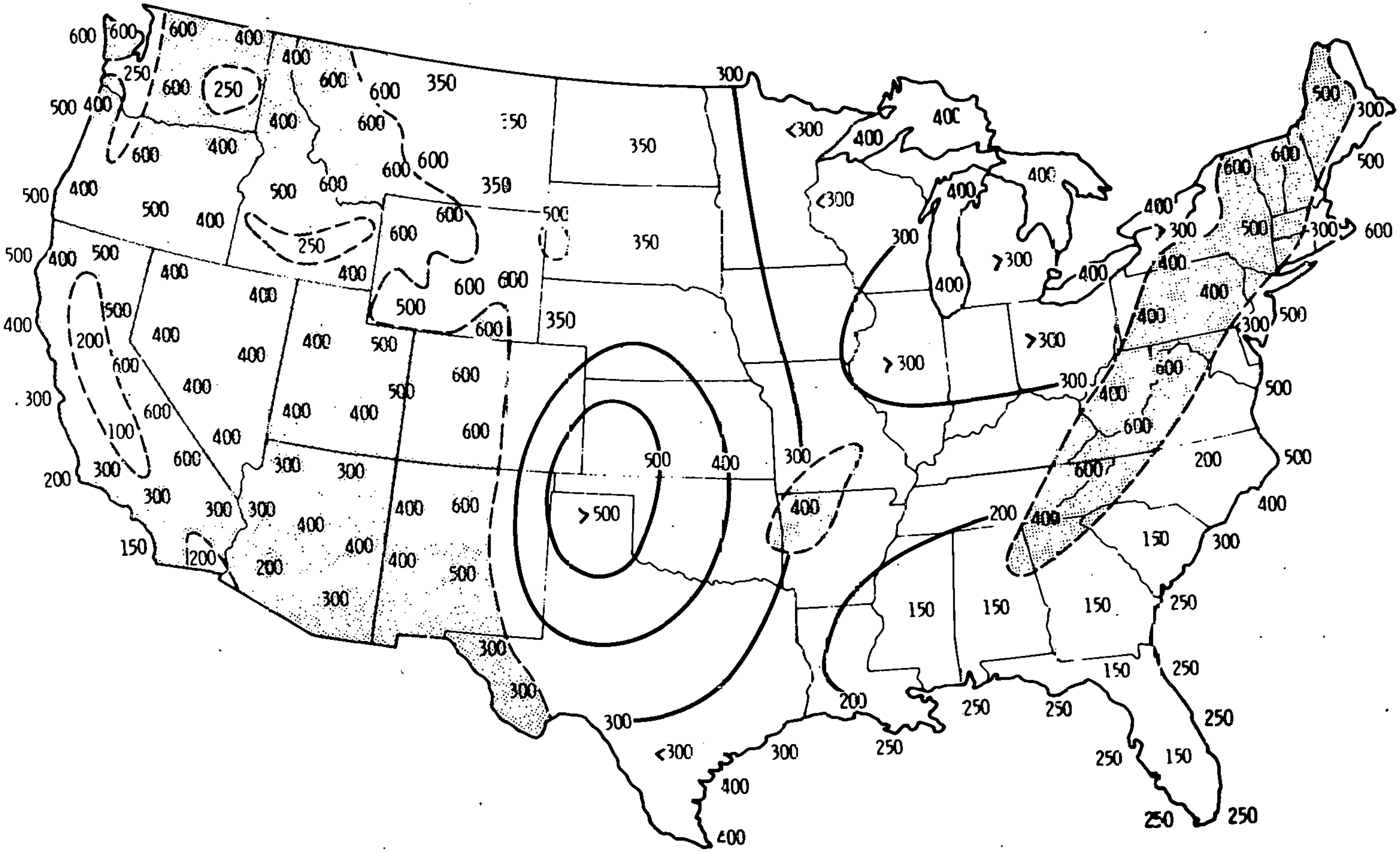
B. Seasonal Wind Availability for Crop Drying

Further analysis of wind power was performed for those states in the first two categories of table 20. In these states, areas where wind power is at least 200 W/m^2 and 300 2 W/m^2 at 20 meters were located. Ten meters was thought to be too low for many wind system applications, while 50 m is probably too high for most farm uses. The latter height would require a large wind turbine, or at least a very high tower, requiring investment costs too great for most farm or elevator establishments. Such systems would more likely be used by utilities or large manufacturing plants.

Because an analysis of mean annual wind power is not sufficient to determine whether this wind power can be harnessed for crop drying, a seasonal analysis also was performed. Typically, wind power is greatest during the winter and spring seasons, whereas most crops are dried in the fall (and sometimes early winter). The poorest months for wind availability are summer and early fall. The way in which wind power varies by season is shown in figures 9 through 12. Wind power estimates in these figures indicate winds of at least 100 W/m^2 during most seasons in most parts of the country, but only at 50 meters. Wind power available at lower heights, while varying seasonally as indicated, is substantially less. The contour maps showing wind power patterns at different heights and the seasonal maps illustrating those patterns at 50 m can be used in conjunction to obtain a general idea of locations with the best wind potential at 20 m during crop-drying seasons. More detailed information is given below.

Table 25 shows mean wind power available at 20 m for months during which grains, tobacco, and peanuts are dried in most states (August through December). At 100 W/m^2, wind power is available in at least some areas in all states during every month (except for August in Maryland and Ohio). Some areas in most states also record winds of over 200 W/m^2, but relatively few stations record wind powers of over 300 W/m^2. Wind power of over 300 W/m^2 is more likely to be available during November and December than during the preceding 3 months.

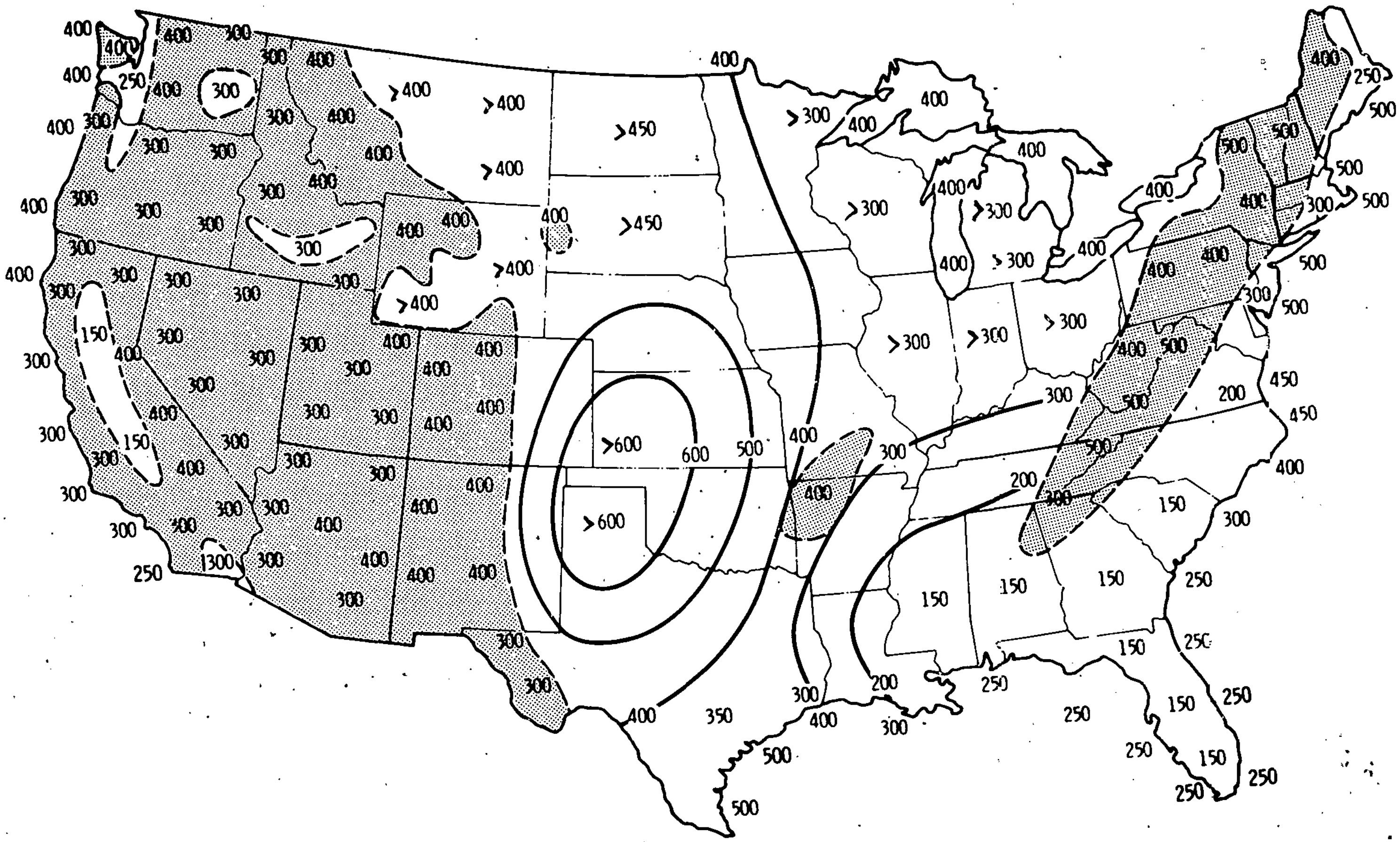
Most of the stations listed in table 25 do not enjoy the specified wind power for the entire season. For example, one station in Delaware records winds with mean monthly power of at least 300 W/m^2 for each month, but it is not necessarily the same station. Table 26 shows the



Note: Over mountainous regions (shaded areas) the estimates are lower limits expected for exposed mountain tops and ridges.

Source: Dennis L. Elliott, "Synthesis of National Wind Energy Assessments," BNWL-2220 (Richland, WA: Battelle, Pacific Northwest Laboratories, July 1977).

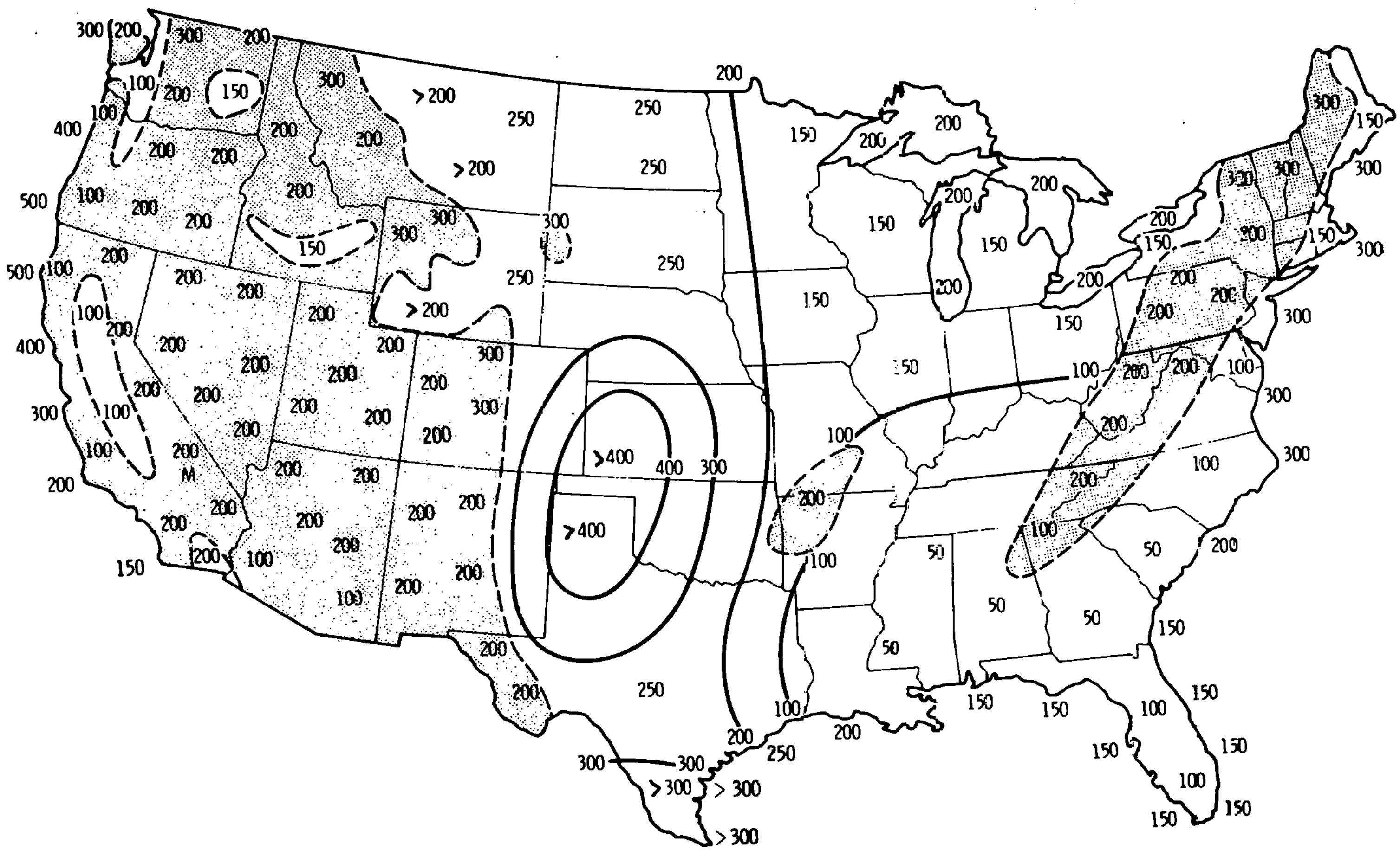
Figure 9. WINTER—AVERAGE WIND POWER (W/m²) ESTIMATED AT 50 m ABOVE EXPOSED AREAS



Note: Over mountainous regions (shaded areas) the estimates are lower limits expected for exposed mountain tops and ridges.

Source: Dennis L. Elliott, "Synthesis of National Wind Energy Assessments," BNWL-2220 (Richland, WA: Battelle, Pacific Northwest Laboratories, July 1977).

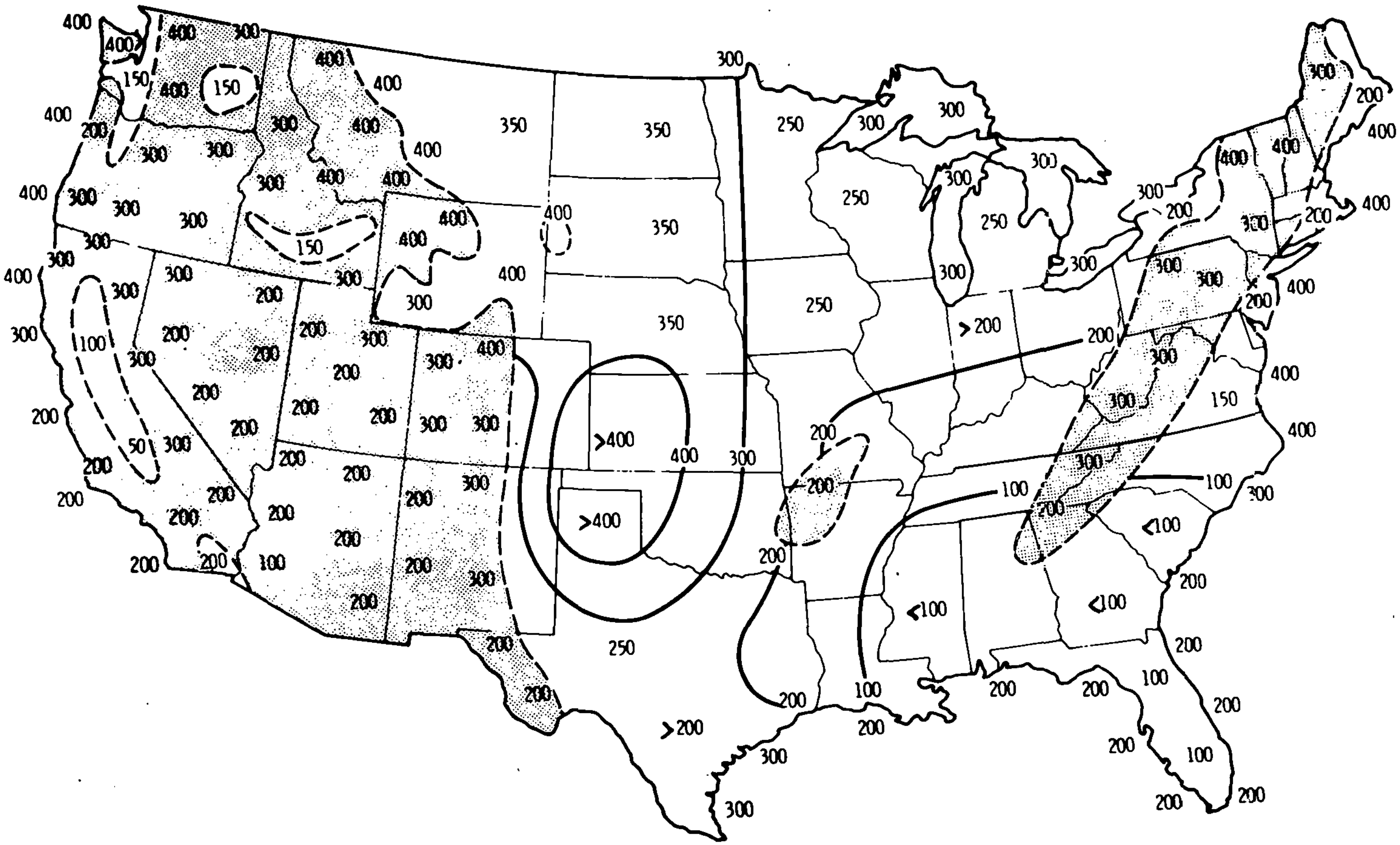
Figure 10. SPRING—AVERAGE WIND POWER (W/m²) ESTIMATED AT 50 m ABOVE EXPOSED AREAS



Note: Over mountainous regions (shaded areas) the estimates are lower limits expected for exposed mountain tops and ridges.

Source: Dennis L. Elliott, "Synthesis of National Wind Energy Assessments," BNWL-2220 (Richland, WA: Battelle, Pacific Northwest Laboratories, July 1977).

Figure 11. SUMMER—AVERAGE WIND POWER (W/m²) ESTIMATED AT 50 m ABOVE EXPOSED AREAS



Note: Over mountainous regions (shaded areas) the estimates are lower limits expected for exposed mountain tops and ridges.

Source: Dennis L. Elliott, "Synthesis of National Wind Energy Assessments," BNWL-2220 (Richland, WA: Battelle, Pacific Northwest Laboratories, July 1977).

Figure 12. FALL—AVERAGE WIND POWER (W/m²) ESTIMATED AT 50 m ABOVE EXPOSED AREAS

Table 25. WIND POWER AVAILABILITY, AUGUST THROUGH DECEMBER, BY STATE

State	Total Stations	Number of Stations with Wind Power Available at: ≥ 100 W/m²					≥ 200 W/m²					≥ 300 W/m²				
		Aug	Sep	Oct	Nov	Dec	Aug	Sep	Oct	Nov	Dec	Aug	Sep	Oct	Nov	Dec
California	65	26	20	18	16	17	12	9	5	3	5	5	2	2	3	3
Colorado	11	9	9	8	8	8	2	2	2	2	1	—	1	—	1	1
Connecticut	3	1	1	2	2	2	—	—	1	1	1	—	—	—	—	—
Delaware	3	1	1	2	3	3	1	1	1	1	1	1	1	1	1	1
Idaho	8	6	7	8	8	7	2	2	1	2	4	—	—	—	—	2
Illinois	13	4	8	11	13	12	—	1	3	9	7	—	—	—	3	3
Indiana	12	2	6	8	12	12	—	—	—	8	6	—	—	—	3	2
Iowa	9	6	7	9	9	9	1	2	3	8	8	—	—	1	2	3
Kansas	13	12	12	12	13	12	7	8	8	8	6	3	4	3	5	3
Maryland	5	—	2	3	4	4	—	—	—	—	1	—	—	—	—	—
Michigan	22	8	16	19	20	19	—	3	6	12	11	—	[illegible]	1	5	4
Minnesota	9	6	7	7	8	7	1	3	3	7	3	—	—	2	3	1
Missouri	14	5	7	9	14	14	—	—	—	3	2	—	—	—	—	—
Nebraska	13	12	12	13	13	13	7	8	8	11	10	—	1	3	6	1
New Mexico	18	15	15	16	14	13	3	2	4	8	8	1	1	1	1	1
North Dakota	7	7	7	7	7	6	2	6	6	6	5	1	1	3	3	5
Ohio	12	—	2	5	11	11	—	—	—	6	6	—	—	—	1	1
Oklahoma	11	10	10	11	11	11	3	5	5	5	6	1	1	1	2	1
Pennsylvania	19	3	5	9	14	16	—	2	3	6	7	—	—	2	4	5
South Dakota	8	8	8	8	8	8	3	6	6	8	6	—	1	1	3	—
Texas	49	29	22	26	39	37	6	4	4	10	8	3	3	3	3	3
Wisconsin	8	2	6	7	8	8	—	—	1	6	3	—	—	—	2	—

Table 26. STATIONS WITH WIND POWER AVAILABLE FOR ENTIRE GRAIN-DRYING SEASON (September—December)

State	Total Stations	Number of Stations with Wind Power Available at:		
		≥100 W/m²	≥200 W/m²	≥300 W/m²
California	65	9	3	1
Colorado	11	7	1	—
Delaware	3	1	1	1
Idaho	8	6	1	—
Illinois	13	8	1	—
Indiana	12	6	—	—
Iowa	9	7	2	—
Kansas	13	12	5	2
Maryland	5	1	—	—
Michigan	22	15	3	—
Minnesota	9	7	3	—
Missouri	14	7	—	—
Nebraska	13	12	7	—
New Mexico	18	12	2	1
Ohio	12	2	—	—
Oklahoma	11	10	5	—
Pennsylvania	19	5	2	—
South Dakota	8	8	6	—
Texas	49	19	3	3
Wisconsin	8	6	—	—

number of stations in each grain-drying state where the specified wind power is available during each month throughout the grain-drying season (September through December). Over half the states listed record winds of over 100 W/m^2 at half or more of their stations for the season, but only two (Nebraska and South Dakota) record winds of more than 200 W/m^2 at over half the stations. Very few stations anywhere record winds above 300 W/m^2 for each of these months. These latter areas include Point Arena, California; coastal Delaware; southern Kansas; Clayton, New Mexico; and the Texas Panhandle. In Texas, winds are good in the Panhandle region during the lengthier grain-harvesting season of that state (July through November or December), and large amounts of corn and soybeans are grown in this area. Also, several stations in the southeastern coastal area of Texas, where corn, soybeans, and rice are harvested, record good winds during fall. However, few of these areas have much wind during summer months.

In general, winds are good during the October-November peanut-drying season in New Mexico and Oklahoma, with most stations in New Mexico and all in Oklahoma recording mean wind power of more than 100 W/m^2 in each month. About one-third of the stations in New Mexico and half those in Oklahoma record mean monthly wind power of over 200 W/m during each month. Only Clayton, New Mexico, and Waynoka, Oklahoma (in the north-western part of the state although not in the Panhandle) enjoy winds with mean monthly power over 300 W/m in October and November. Peanuts in Texas, unlike grains, tend to be grown more in the central parts of the state, with a harvesting season extending from July into December. In these areas, winds are low (generally under 100 W/m^2) during the months of July, August, and September.

Based on seasonal data, the use of wind energy for tobacco curing seems less feasible than its application in grain or peanut drying. Relatively few stations in states where tobacco is cured record data indicating wind powers of over 100 W/m^2 during all the curing months of August through October, with August the calmest month. No stations record winds of over 200 W/m^2 during all these months, and only Connecticut, Pennsylvania, and Wisconsin record winds above 200 W/m^2 during any part of this period. Areas where wind power exceeds 100 W/m^2 for the season do not coincide with tobacco-growing areas, except for in southern Pennsylvania (Woodward) and northwestern Missouri (Kansas City and Knoxville).

The dehy production season is longer than that of the other crops under study; it extends from April through November in most states, with the bulk of production between May and October. Table 27 shows wind power availability at 20 m for the months of April through July, for states where dehy is produced. Tables 25 and 27 together can be used to judge approximate wind power availability during the entire season. Again, the stations listed may not have winds of the specified powers during each month. Table 28 shows the number of stations recording the specified wind powers during each month from May through October. States where over half the stations have wind powers of at least 100 W/m^2 each month include Colorado, Idaho, Iowa, Kansas, Minnesota, Nebraska, New Mexico, North and South Dakota, and Oklahoma. Nearly half the stations have wind powers

Table 27. WIND POWER AVAILABILITY, APRIL THROUGH JULY, FOR STATES WITH DEHY FACILITIES

State	Total Stations	Number of Stations with Wind Power Available at: ≥100 W/m²				≥200 W/m²				≥300 W/m²			
		Apr	May	Jun	Jul	Apr	May	Jun	Jul	Apr	May	Jun	Jul
California	65	39	45	43	33	18	18	16	14	13	13	13	8
Colorado	11	11	11	9	9	9	6	6	—	4	4	3	—
Idaho	8	8	8	8	8	7	6	4	2	3	2	2	—
Illinois	13	13	12	10	2	11	2	2	—	8	—	—	—
Indiana	12	12	11	8	3	10	3	1	—	4	—	—	—
Iowa	9	9	9	9	5	9	6	4	1	7	3	1	—
Kansas	13	13	13	12	12	12	11	9	7	11	7	7	2
Maryland	5	5	3	1	1	3	—	—	—	—	—	—	—
Michigan	22	22	21	18	9	16	6	2	—	3	1	—	—
Minnesota	9	8	8	7	6	7	7	4	—	5	4	—	—
Missouri	14	14	13	11	4	13	1	1	—	2	1	—	—
Nebraska	13	13	13	13	13	13	12	11	6	11	10	5	—
New Mexico	18	18	18	18	16	17	16	16	5	14	8	7	1
North Dakota	7	7	7	7	7	6	6	5	2	6	6	1	1
Ohio	12	12	10	5	1	7	1	—	—	1	—	—	—
Oklahoma	11	11	11	11	10	11	10	8	3	9	6	6	1
Pennsylvania	19	19	12	5	3	9	3	2	—	4	1	—	—
South Dakota	8	8	8	8	7	8	8	7	3	8	5	2	—
Texas	49	49	46	44	36	40	31	27	11	18	12	9	4
Wisconsin	8	8	8	6	5	6	5	—	—	4	1	—	—

Table 28. STATIONS WITH WIND POWER AVAILABLE FOR MAIN DEHY PRODUCTION SEASON (May-October)

State	Total Stations	Number of Stations with Wind Power Available at:		
		≥100 W/m²	≥200 W/m²	≥300 W/m²
California	65	13	4	1
Colorado	11	7	1	—
Idaho	8	6	1	—
Illinois	13	2	—	—
Indiana	12	1	—	—
Iowa	9	5	1	—
Kansas	13	12	6	2
Maryland	5	—	—	—
Michigan	22	8	—	—
Minnesota	9	6	—	—
Missouri	14	3	—	—
Nebraska	13	12	6	—
New Mexico	18	13	2	—
North Dakota	7	7	2	1
Ohio	12	—	—	—
Oklahoma	11	10	3	1
Pennsylvania	19	3	—	—
South Dakota	8	7	3	—
Texas	49	19	3	2
Wisconsin	8	2	—	—

ave wind powers greater than 200 W/m^2 in Kansas, Nebraska, and South Dakota. Locations with wind power consistently greater than 200 W/m^2 include Point Arena, California, southwestern Kansas, southeastern North Dakota, northwestern Oklahoma, and the Texas Panhandle.

C. Summary

The states that show the most potential for wind power application in crop drying, based both on the number of drying establishments and the seasonal availability of wind power, are the midwestern states. These states dry substantial amounts of corn, soybeans, and other grains. Illinois, Indiana, Iowa, Minnesota, Missouri, and Nebraska lead in terms of numbers of drying facilities and volume of corn and soybeans dried. The midwestern states also have relatively large numbers of alfalfa dehydration facilities; over half the dehy operations in the country are located in Nebraska and Kansas. Further south and west, peanuts are dried in New Mexico, Oklahoma, and Texas; and rice in Texas and California. The major peanut- and tobacco-producing states in the Southeast (some of these states also grow rice) were eliminated from the study because of very poor wind potential. The major tobacco states remaining are Maryland, Pennsylvania, and Wisconsin; Connecticut and a few midwestern states also grow tobacco.

The leading areas in terms of wind potential are Kansas, Nebraska, the Dakotas, northwestern Oklahoma, and the Texas Panhandle. The area encompassing the Texas Panhandle, northwestern Oklahoma, and southwestern Kansas is a particularly good area for winds. Other midwestern states with good wind power potential include Illinois, Indiana, Iowa, Michigan, Minnesota, and parts of Wisconsin and Missouri. Colorado, Idaho, and New Mexico have good winds, although less crop drying occurs in these areas. The more eastern grain-drying states of Delaware, Ohio, Maryland, and Pennsylvania do not have as much wind potential as the midwestern and western regions. California's winds occur primarily in the mountainous and coastal areas, whereas most crops are grown in the central valleys.

The seasonal availability of wind power in many regions does not coincide with crop-drying requirements. Winds generally are best in winter and spring, while most crops are dried in the fall. The tobacco-curing season is particularly illsuited to take advantage of wind power, since it usually includes the month of August. The summer months are the poorest months for wind availability. Dehy production also occurs during the summer (from late spring into fall) in most areas. Nevertheless, wind systems still might be operated on a supplemental basis in areas where winds are available for only a part of the season.

IV. ECONOMIC ANALYSIS

The objective of the economic analysis was to derive the maximum price a user should be willing to pay to purchase a wind energy conversion system (WECS) for use in crop drying (breakeven cost), and to compare this price with currently projected prices of commercially available wind machines. Below, the assumptions and methodology employed to determine breakeven costs, the sizes and numbers of WECS required for various drying operations, and the feasibility of installing WECS given their projected costs are described. Crop-drying energy requirements determined in section II and the expected output of different sizes of WECS in various wind regimes are inputs to these analyses.

A. Breakeven Costs

The first step in the determination of breakeven costs was to calculate seasonal (annual) electricity and fossil fuel costs for various kinds and sizes of crop dryers described in the previous sections. These seasonal costs, derived from the energy requirement data presented in section II (tables 9, 13, 15, 17, and 18) are presented in tables 29 through 32. Energy prices assumed were:

Electricity:	4.12¢/kWh
Natural Gas:	198.80¢/000 cf
LPG:	29.30/gal¢
	48.20/gal¢
Fuel Oil No. 6:	45.70/gal¢

The electricity price is the 1978 average revenue per kWh of Rural Electrification Administration borrowers operating distribution systems, for small commercial/industrial establishlments.[4] This price is between the average retail electricity prices listed by DOE for residential (4.91¢/kWh) and industrial (3.11¢/kWh) establishments in July 1979.[15] The natural gas price is the average price to industrial users as of July 1979, and the LPG prices are July 1979 average wholesale and residential prices, respectively. The residential LPG price was used as well as the wholesale price because it is closer to prices assumed in recent crop-drying studies, which range from 40¢ to 54¢/gal.[9, 16] The July 1979 average wholesale price of fuel oil No. 6 was used.[17]

Present values of these seasonal costs (the present value of the benefits or savings if these conventional energy sources were replaced) then were calculated over a period of 20 years (the assumed lifetime of the WECS), with a discount rate of 10 precent. Fossil fuel costs were assumed to escalate at a rate of 35 percent for the first 2 years and at 8 percent annually thereafter; electricity costs were assumed to rise 20 percent annually for the first 2 years and 4 percent per year thereafter.*

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* Energy price escalation rates suggested by USDA and DOE.

Table 29. SEASONAL GRAIN-DRYING ENERGY COSTS

System	Size (bu/yr)	Seasonal Energy Costs ($): Natural Gas	LPG[a] (1)	LPG[a] (2)	Electricity	Total NG + Electricity	Total: LPG + Electricity (1)	Total: LPG + Electricity (2)
Batch in bin	7,500	199	352	578	21	220	373	599
	37,500	1,014	1,729	2,844	107	1,120	1,836	2,951
Portable batch	10,000	238	410	675	12- 22	250-260	422- 432	687- 697
	25,000	616	1,026	1,687	185-361	801-977	1,211-1,387	1,872-2,048
Continuous flow	30,000	795	1,348	2,217	50	845	1,398	2,267
	50,000	1,312	2,227	3,663	84	1,396	2,311	3,747
	200,000	5,268	8,907	14,653	309	5,577	9,216	14,962
	1,000,000	26,381	44,565	73,312	1,648	28,029	46,213	74,960
	3,000,000	79,162	133,667	219,888	4,944	84,106	138,611	224,832
In-storage layer	2,000	40	59	96	26	66	85	122
	13,000	219	352	578	133	352	483	711
In-storage layer, electric heated only	2,000	—	—	—	55-140	—	—	—
	13,000	—	—	—	364-927	—	—	—
Rice dryers	1,000,000	4,890	8,263	13,592	1,281	6,171	9,544	14,873
	5,000,000	23,796	40,170	66,082	6,588	30,384	46,758	72,670

[a]Costs are estimated for LPG at two different prices (see text).

Table 30. SEASONAL PEANUT-DRYING ENERGY COSTS[a]

Amount Dried (cwt/yr)	Seasonal Energy Costs ($)						
	Natural Gas	LPG[b] (1)	LPG[b] (2)	Electricity	Total NG + Electric	Total: LPG + Electric (1)	Total: LPG + Electric (2)
3,840	245	410	675	177	422	587	852
10,000	636	1,055	1,735	461	1,097	1,516	2,196
50,000	3,181	5,333	8,772	2,303	5,484	7,636	11,075
100,000	6,362	10,665	17,545	4,606	10,968	15,271	22,151
300,000	19,085	31,996	52,634	13,818	32,903	45,814	66,452

[a]Initial moisture content of 20% assumed; final moisture content of 10%.

[b]Requirements and costs are estimated for LPG at two different prices (see text).

Table 31. SEASONAL TOBACCO—DRYING ENERGY COSTS

Type Barn	Seasonal Energy Costs						
	LPG[a] (1)	LPG[a] (2)	Fuel Oil	Electricity	Total LPG + Electric (1)	Total LPG + Electric (2)	Total Fuel Oil + Electric
Bulk	401-686	660-1,128	375-644	15-22	549- 908	808-1,350	523- 866
Conventional	428-858	704-1,412	470-804	15-22	576-1,030	852-1,634	618-1,026

[a]LPG costs estimated using two different prices (see text).

Table 32. SEASONAL FORAGE-DRYING ENERGY COSTS

Production (tons/season)	Seasonal Energy Costs ($)		
	Natural Gas	Electricity	Total
1,000	23,856	5,150	29,006
2,000	47,712	10,259	57,971
3,000	71,568	15,368	86,936
4,000	95,424	20,476	115,900
5,000	119,280	25,626	144,906

Present values of energy savings were calculated from the formula:

$$PV = \sum_{t=1}^{20} e_t \frac{1}{(1+r)^t} \qquad (1)$$

where PV = present value

e_t = annual energy savings

r = 0.10 = discount rate

t = time period (year)

Using the resulting present values, the allowable investment cost or breakeven cost for WECS were calculated. Breakeven costs were assumed to be the purchase price that equated the present value of the savings generated (the fossil fuel and electricity costs saved) to the present value of the annual costs associated with WECS. Assumptions were that (1) operations and maintenance costs (including property taxes and other miscellaneous costs) are 5 percent of fixed costs, and (2) the WECS have a salvage value of zero at the end of the 20-year lifetime. The equation for calculating the present value of the annual costs then was:

$$AC = X + \sum_{t=1}^{20} aX/(1+r)^t \qquad (2)$$

where AC = annual costs;

X = breakeven costs (investment cost or price WECS allowed)

a = 0.10 = 0.05 annual depreciation + 0.05 operations and maintenance;

r = 0.10 = discount rate;

t = time period (year)

Setting a = 0.10 for each year, the last term in equation (2) becomes a constant: AC = X + 0.851X = 1.851X. (3)
Annual costs then are set equal to benefits, or the present value of savings, from equations (1) and (3);

PV = AC = 1.851X. (4)
Thus, breakeven costs (X) are equal to the present value of savings divided by 1.851.

Breakeven costs were calculated assuming the displacement of conventional energy sources by wind energy for the drying systems presented in tables 29 through 32. (Where a range of seasonal energy costs were calculated in tables and 31, a midpoint value was used to calculate breakeven costs.) Variations of these base cases can be envisioned easily. For instance, a wind machine might be used to generate only a part of the electricity or thermal energy required. This scenario is a likely one, since WECS are more likely to be used on a supplemental basis rather than as stand-alone systems. Because energy storage is so expensive, WECS might well be used when the wind is blowing, with conventional sources used as backup. In some crop-drying applications (e.g., continuous flow and portable batch grain dryers, alfalfa dr,ying operations, and tobacco barns), WECS would be most useful as a supplemental source because of the high temperatures required. If wind power were used to drive a heat pump, some combination of the base case breakeven costs listed might be relevant. For instance, a wind turbine could be coupled to a heat pump to provide heat for drying, refrigeration for cooling, or both simultaneously on different batches of the crop. WECS thus might be able to supply both some of the electrical requirements and some of the thermal energy requirements.

The breakeven costs presented in tables 33 through 36 reflect current energy usage, and obviously are greater (a) the higher the price of conventional energy, and (b) the higher the energy requirements. For a given type of system, both energy requirements and costs tend to rise linearly with the increase in the amount of crop being dried--there are few if any economies of scale as this amount increases. Because of the differences in price among fossil fuels on a heat-equivalent basis, systems using natural gas would allow a lower maximum investment for replacement of this energy source than systems using LPG and fuel oil. Replacement of a fossil fuel with another heat source always would be most economically feasible in a system using the higher priced LPG.

Once breakeven costs were determined, a payback analysis was performed, presenting annual outlays required for WECS operation and resulting savings in conventional energy costs for these systems. Although WECS lifetimes were assumed to be 20 years, loan periods were assumed to be 10 years. Interest rates of 9 and 10 percent were assumed, as were loans of both 20 percent and 50 percent equity. Payback periods were analyzed assuming an investment equal to the allowable costs listed in tables 33 through 36.

Payback (the point at which total accrued savings equaled or exceeded total outlays) occurred between the ninth and twelfth years. Over the 20-year lifetime assumed for the WECS, savings were about double the outlays. There was little sensitivity to changes in percent equity or to the one percent change in interest rate; the largest difference between the most and least favorable cases (50 percent equity, 9 percent interest; and 20 percent equity, 10 percent interest, respectively) was 2 years. Some examples of the payback analyses are presented in appendix C.

B. Breakeven Costs versus Projected WECS Costs

WECS Energy Output

The first step in comparing breakeven costs with currently projected wind system costs was to calculate power output for different sizes of WECS. The systems selected were small wind energy systems (SWECS) tested at Rocky Flats,

Table 33. BREAKEVEN COSTS FOR WECS SUPPLYING ELECTRICITY AND HEAT TO GRAIN DRYERS (Total Seasonal Demand)

System	Size (bu/yr)	Breakeven Costs ($000) Assuming Displacement of: Natural Gas	Low-Priced LPG	High-Priced LPG	Conventional Electricity
Batch in bin	7,500	2.8	4.9	8.0	0.2
	37,500	14.0	23.9	39.4	0.9
Portable batch	10,000	3.3	5.7	9.3	0.1
	25,000	8.5	14.2	23.3	2.4
Continuous flow	30,000	11.0	18.7	30.7	0.4
	50,000	18.2	30.8	50.7	0.7
	200,000	72.9	123.2	202.7	2.6
	1,000,000	365.0	616.6	1,014.4	13.7
	3,000,000	1,095.3	1,849.5	3,042.5	41.1
In-storage layer	2,000	0.5	0.8	1.3	0.2
	13,000	3.0	4.9	8.0	1.1
In-storage layer, electric dried only	2,000	—	—	—	0.8
	13,000	—	—	—	5.4
Rice dryers	1,000,000	67.7	114.3	188.1	10.7
	5,000,000	329.3	555.8	914.3	54.8

Table 34. BREAKEVEN COSTS FOR WECS SUPPLYING ELECTRICITY AND HEAT TO PEANUT DRYERS (Total Seasonal Demand)

Size (cwt/yr)	Breakeven Costs ($000) Assuming Displacement of:			
	Natural Gas	Low-Priced LPG	High-Priced LPG	Conventional Electricity
3,840	3.4	5.7	9.3	1.5
10,000	8.8	14.6	24.0	3.8
50,000	44.0	73.8	121.4	19.2
100,000	88.0	145.6	242.8	38.3
300,000	264.1	442.7	728.3	114.9

Table 35. BREAKEVEN COSTS FOR WECS SUPPLYING ELECTRICITY AND HEAT TO TOBACCO BARNS (Total Seasonal Demand)

Type Barn	Breakeven Costs ($000) Assuming Displacement of:			
	Fuel Oil	Low-Priced LPG	High-Priced LPG	Conventional Electricity
Bulk[a]	7.1	7.5	12.4	0.2
Conventional	8.8	8.4	14.6	0.2

[a]1,250 cubic feet; five-foot-deep boxes in bulk barn.

Table 36. BREAKEVEN COSTS FOR WECS SUPPLYING ELECTRICITY AND HEAT TO FORAGE DRUMS (Total Seasonal Demand)

Size (tons/yr)	Breakeven Costs ($000) Assuming Displacement of:	
	Natural Gas	Conventional Electricity
1,000	330.1	42.8
2,000	660.2	85.3
3,000	990.3	127.8
4,000	1,320.3	170.3
5,000	1,650.4	213.1

all of which were rated at 20 miles per hour.[18] Data from these systems were used because comparable power curves were available. These systems were not commercially available as of September 1979, although some other systems of comparable size were (where "commercially available" is defined as production of at least three units, one of which is operational).[19] Comparable power curves were not available for the commercially available systems. The systems from which data were obtained for this report are listed in appendix D.

Mean power output was calculated using the Rayleigh distribution and the power curves supplied by Rocky Flats. The probability density function for the Rayleigh distribution is given by:

$$F(V) = \pi/2 \frac{V}{\bar{V}^2} \exp - \left[\pi/4 \left(\frac{V}{\bar{V}}\right)^2\right]$$

where:

V = wind velocity

$\bar{V}$ = site mean wind velocity

Mean outputs were calculated for three average wind speeds: 4.4 meters per second (m/s) (100 W/m^2); 5.6 m/s (200 W/m^2); and 6.4 m/s (300 W/m^2). (Very few stations record wind speeds higher than 6.4 m/s at 20 m, and 50 m is expected to be too high for most turbines installed for farm use.) For each assumed average speed V, the frequency of occurrence for each speed V (given by the above function) was multiplied by the power produced by the WECS at that speed (obtained from the power curves). These values then were summed for total mean power output in kW, and multiplied by the appropriate number of seasonal hours. Resulting figures were mutliplied by 0.9, based on the assumption that a turbine would be available for service 90 percent of the time the wind is in the operating range.[20] Capacity factor (mean power output/rated power) and mean power output/power in the wind also were calculated. Table 37 presents performance for small wind systems of different power ratings (where different systems of a given rating had been tested, their results were averaged), including annual energy output. Table 38 shows energy output over shorter time periods.

Comparison with Projected WECS Costs

Using the crop-drying energy requirements presented in section II and the energy output of different sizes of SWECS (tables 37 and 38), it was determined what SWECS or combinations of SWECS would be required to satisfy the energy requirements in the different wind regimes. Projected costs for SWECS obtained from Rocky Flats (see table 39) were compared with breakeven costs. Site preparation and installation costs are not included in table 39, and would depend on the specific site as well as the size and type of machine. Estimates for SWECS site preparation and installation range between several hundred and two to three thousand dollars. In addition, no storage costs are included.

Table 37. PERFORMANCE STATISTICS FOR GENERIC WIND SYSTEMS AT 3 MEAN WIND VELOCITIES[a]

System Rated kW	Mean Power (kW)	Capacity Factor	Mean Power/ Power in Wind	Annual Energy[b] (kWh)	× 0.9
			4.4 m/s (100 W/m²)		
1	0.184	0.18	0.11	1,600	1,500
2	0.556	0.28	0.28	4,900	4,400
8	1.748	0.22	0.23	15,300	13,800
40	5.779	0.15	0.21	50,600	45,500
			5.6 m/s (200 W/m²)		
1	0.357	0.36	0.11	3,100	2,800
2	0.930	0.47	0.24	8,100	7,300
8	3.221	0.40	0.21	28,200	25,400
40	11.200	0.28	0.23	98,100	88,300
			6.4 m/s (300 W/m²)		
1	0.476	0.48	0.10	4,200	3,800
2	1.171	0.59	0.20	10,300	9,200
8	4.219	0.53	0.18	37,000	33,300
40	14.836	0.37	0.18	130,000	117,000

[a]Where more than one system of a given rating was analyzed, an average of the mean powers obtained from the different systems is presented.
[b]Rounded to nearest hundred.

Table 38. ENERGY OUTPUT OVER DIFFERENT TIME PERIODS FOR GENERIC WIND SYSTEMS AT 3 MEAN WIND VELOCITIES

System Rated kW	Energy Output (kWh)[a] over: 1 Month	6 Weeks	2 Months	3 Months	6 Months
			4.4 m/s (100 W/m²)		
1	130	190	250	380	760
2	370	550	730	1,100	2,200
8	1,150	1,730	2,300	3,450	6,900
40	3,790	5,690	7,580	11,370	22,750
			5.6 m/s (200 W/m²)		
1	230	350	470	700	1,400
2	610	920	1,220	1,830	3,650
8	2,120	3,180	4,230	6,350	12,700
40	7,360	11,040	14,720	22,080	44,150
			6.4 m s (300 W/m²)		
1	320	480	630	950	1,900
2	770	1,160	1,540	2,310	4,600
8	2,780	4,170	5,560	8,340	16,650
40	9,750	14,630	19,500	29,250	58,500

[a]Includes 0.9 operational factor.

Table 39. PROJECTED SWECS FOB PRICES ($)

Rated Power (kW)	10th Unit	100th Unit	10,000th Unit
2	5,700	3,600	3,100
8	20,000	10,000	8,000
40	50,000	25,000	20,000

Source: Rockwell International Corporation, Wind Systems Program, Rocky Flats Plant, Energy System Group, "Systems Summary of Small Wind Energy Conversion Systems (SWECS) Development," 1979.

Tables 40 through 43 show these SWECS requirements and the ratio of SWECS cost projected at the 10,000th unit to breakeven costs (from tables 33 through 36). The comparisons focus on the replacement of electricity, although the supply of supplemental heat, particularly with the use of a heat pump, also would be a possible application. Even for systems where high temperatures were not required and wind turbines would supply all the heat now provided by fossil fuels, unreasonably large numbers of the small turbines would be required. For example, even for a small in-storage-layer system, two 40-kW wind machines would be required to furnish sufficient heat (assuming 3,600 kJ, or 3,412 Btu, per kWh) in a wind regime of 100 W/m^2, assuming the dryer operated over a 6-week period. To supply all heat to the larger crop dryers, use of a larger WECS should be more economical than the SWECS analyzed in this report.

Tables 40 through 43 show comparisons only for the wind regimes of 100 W/m^2 and 300 W/m^2, the least and most favorable wind conditions analyzed, respectively. Six weeks is the time period used, except for alfalfa dehy. The problem with crop drying, with respect to use of SWECS, is that it usually takes place for a relatively short time during the year. For corn and soybean drying, one to 2 months are the most likely scenarios, although some low-temperature drying might continue over 3 months. As noted in section II-G, the rice harvesting and drying season can last from 3 to 6 months; peanut harvesting/drying from 2 to 6 months; and tobacco curing from 2 to 3 months. Nevertheless, most individual dryers are not operated for an entire season; the larger commercial facilities are more likely to operate for longer periods of time. In the case of tobacco, five cures per season per barn, each lasting a week or less, are the average. Alfalfa dehy is produced during several months in many states and all year long in California; therefore, table 43 shows data for a 6-month period as well as for 6 weeks. Again, however, most individual facilities may operate for under 6 months.

The comparisons of projected SWECS cost to breakeven costs indicate the SWECS are not economically viable for any system if operated only for a 6-week period. At best, the projected costs are about four times the calculated breakeven costs. For alfalfa dehy facilities operating over 6 months, however, the projected costs (exclusive of site preparation, installation, and storage costs) with average available wind power of 300 W/m^2 do come close to breakeven. Other types of drying systems, if they could be operated over that length of time, also could be marginally feasible. Operation of most systems over 3 months in areas with wind power averaging 300 W/m^2 still would result in a ratio of projected to breakeven costs of greater than two.

C. Summary

With the projected costs and energy prices assumed, the installation of WECS would not be viable for most crop-drying systems. However, changes in these parameters could result in an analysis more favorable to WECS use. For instance, the baseline conventional energy prices used were national averages. These prices vary substantially by region, and many farmers probably are paying substantially higher prices. Further, the prices used in this study, which were the most recently compiled statistics available, lag current energy prices by a few months. Conventional energy prices, of course may escalate either more or less rapidly than the rates assumed.

Table 40. NUMBER, SIZE, AND RATIO OF PROJECTED TO BREAKEVEN COST OF SWECS REQUIRED TO SUPPLY ELECTRICITY FOR GRAIN DRYING OVER A 6-WEEK PERIOD

Type System	Size (bu/yr)	Average Wind Power = 100 W/m²: SWECS #	Average Wind Power = 100 W/m²: Required[a] Size (kW)	Average Wind Power = 100 W/m²: SWECS Cost[b]/ Breakeven Cost	Average Wind Power = 300 W/m²: SWECS #	Average Wind Power = 300 W/m²: Required Size (kW)	Average Wind Power = 300 W/m²: SWECS Cost[b]/ Breakeven Cost
Batch in bin	7,500	1	2	15.5	1	1	—
	37,500	2	8	8.9	3	2(2),1	—
Portable batch	10,000	1	2	31.0	1	1	—
	25,000	1	40	8.3	2	2,8	4.6
Continuous flow	30,000	1	8	20.0	1	2	7.8
	50,000	2	8,2	15.9	2	2	8.9
	200,000	2	40,8	10.8	2	8	6.2
	1,000,000	7	40	10.2	3	40	4.4
	3,000,000	21	40	10.2	9	8(1),40(8)	4.1
In-storage layer	2,000	1	2	15.5	1	2	15.5
	13,000	2	8	14.6	1	8	7.3
In-storage layer, electric dried only	2,000	1-2	8	10.0-20.0	1	2-8	10.0
	13,000	2-4	40	7.4-14.8	2	8-40	3.0-7.4
Rice dryers	1,000,000	6	40	11.2	3	8(1),40(2)	4.5
	5,000,000	28	40	10.2	11	40	4.0

[a] Numbers of SWECS required should be regarded as approximate, since estimates of energy requirements and of SWECS output both are only approximate. Configurations of SWECS different from those listed here are possible. In many cases, surplus electricity would be available with the configurations listed.
[b] Costs were projected for the 10,000th unit, from table 39. Projected costs for 1-kW machines were not available, but probably would be around or slightly below the 2-kW machine cost.

Table 41. NUMBER, SIZE, AND RATIO OF PROJECTED TO BREAKEVEN COST OF SWECS REQUIRED TO SUPPLY ELECTRICITY FOR PEANUT DRYING OVER A 6-WEEK PERIOD[a]

	Average Wind Power = 100 W/m^2			Average Wind Power = 300 W/m^2		
Size (cwt/yr)	SWECS #	Required[b] Size	SWECS Cost[c]/ Breakeven Cost	SWECS #	Required[b] Size	SWECS Cost[c]/ Breakeven Cost
3,840	1	40	13.3	1	8	5.3
10,000	2	40	10.5	1	40	5.3
50,000	10	40	10.4	4	40	4.2
100,000	20	40	10.4	8	40	4.2
300,000	59	40	10.3	23	40	4.0

[a]Initial moisture content of 20% assumed.
[b]Numbers of SWECS required should be regarded as approximate, since estimates of energy requirements and of SWECS output both are only approximate. Configurations of SWECS different from those listed here are possible. In many cases, surplus electricity would be available with the configurations listed.
[c]Costs were projected for the 10,000th unit, from table 39. Projected costs for 1-kW machines were not available, but probably would be around or slightly below the 2-kW machine cost.

Table 42. NUMBER, SIZE, AND RATIO OF PROJECTED TO BREAKEVEN COST OF SWECS REQUIRED TO SUPPLY ELECTRICITY FOR TOBACCO CURING OVER A 6-WEEK PERIOD

	Average Wind Power = 100 W/m^2			Average Wind Power = 300 W/m^2		
Type Barn	SWECS #	Required[a] Size	SWECS Cost[b]/ Breakeven Cost	SWECS #	Required[a] Size	SWECS Cost[b]/ Breakeven Cost
Bulk	1	2	15.5	1	1	—
Conventional	1	2	15.5	1	1	—

[a]Numbers of SWECS required should be regarded as approximate, since estimates of energy requirements and of SWECS output both are only approximate. Configurations of SWECS different from those listed here are possible. In many cases, surplus electricity would be available with the configurations listed.
[b]Costs were projected for the 10,000th unit, from table 39. Projected costs for 1-kW machines were not available, but probably would be around or slightly below the 2-kW machine cost.

Table 43. NUMBER, SIZE, AND RATIO OF PROJECTED TO BREAKEVEN COST OF SWECS REQUIRED TO SUPPLY ELECTRICITY FOR FORAGE DRYING OVER 6 WEEKS AND 6 MONTHS

	Average Wind Power = 100 W/m²			Average Wind Power = 300 W/m²		
Size (tons/yr)	SWECS #	Required[a] Size	SWECS Cost[b]/ Breakeven Cost	SWECS #	Required[a] Size	SWECS Cost[b]/ Breakeven Cost
			6 Weeks			
1,000	22	40	10.3	9	40	4.2
2,000	44	40	10.3	17	40	4.0
3,000	66	40	10.3	26	40	4.1
4,000	88	40	10.3	34	40	4.0
5,000	109	40	10.2	43	40	4.0
			6 Months			
1,000	6	40	2.8	3	8(1),40(2)	1.1
2,000	11	40	2.6	5	8(1),40(4)	1.0
3,000	17	40	2.7	8	8(2),40(6)	1.1
4,000	22	40	2.6	9	40	1.1
5,000	28	40	2.6	11	40	1.0

[a]Numbers of SWECS required should be regarded as approximate, since estimates of energy requirements and of SWECS output both are only approximate. Configurations of SWECS different from those listed here are possible. In many cases, surplus electricity would be available with the configurations listed.

[b]Costs were projected for the 10,000th unit, from table 39. Projected costs for 1-kW machines were not available, but probably would be around or slightly below the 2-kW machine cost.

The major problem with crop drying is that it occurs for only a short time during the year. According to this analysis, WECS are not viable unless drying systems are operated over a period of at least 6 months. If drying were a year-round activity, WECS costs projected at the 10,000th unit would be below breakeven costs. Thus WECS should be economically viable if used for other farm applications during that part of the year outside the drying season. Because of the current high cost of long-term energy storage, as well as the intermittent nature of the wind, the use of wind systems on a supplemental basis probably will be preferable to their use as stand-alone systems.

Because electricity is more expensive than fossil fuels (on a heat- or kWh-equivalent basis), WECS should be able to replace electricity more economically than fossil fuels. With the energy prices assumed in this analysis, electricity is over six times as expensive as natural gas, about four times as expensive as the higher prices residential LPG. The assumption of higher escalation rates for fossil fuels than for electricity generated from oil or natural gas will continue to be significantly generated from oil or natural gas will continue to be significantly more expensive than the fuels themselves. The drying systems most compatible with wind power, then, are those requiring relatively low temperatures over a fairly long period of time, such as the low-temperature drying of grains and peanuts. Portable batch and continuous flow grain dryers are less likely candidates, because they are structured to dry the crop quickly at high temperatures. Tobacco curing and forage drying also require high temperatures. WECS might be used, particularly with a heat pump, to provide supplemental heat in drying these crops.

Even if projected WECS costs approach breakeven costs, the payback periods of 9 to 12 years are fairly long. Further, there is not much sensitivity due to changes in the percent of equity on loans or to small changes in interest rates. Weather or not these lengths of payback are acceptable depends on the time horizon of farmers or other individuals or corporations investing in the WECS.

V. SUMMARY AND CONCLUSIONS

Crop-drying facilities are most numerous in the midwestern and southeastern states. The largest grain-producing and grain-drying region is the Midwest. Those midwestern states with the largest estimated numbers of drying facilities include Illinois (about 70,000), Iowa (60,000), Missouri, Minnesota, and Indiana (close to 30,000 each). The southeastern states, particularly North Carolina, also produce and dry substantial quantities of grains; several drying facilities are located in the middle-Atlantic states, and a few in the West. In addition, rice is dried in the Southwest as well as in the Southeast. Although many grains are dried artificially, by volume corn and soybeans are the most important of these. Rice production is less than that of corn and soybeans, but very nearly all rice now is artificially dried.

Peanuts are grown and dried in the Southeast, some middle-Atlantic states, and the Southwestern states of New Mexico, Oklahoma, and Texas. Tobacco curing occurs predominantly in the Southeast, the middle-Atlantic, and the midwestern states of Indiana, Missouri, Ohio, and Wisconsin. Shade tobacco is grown in Connecticut. Although forages no longer are dried artificially to any great extent because of the energy expense, several alfalfa dehydration facilities still are operated. States with the largest numbers of dehy operations include Nebraska, Kansas, and California. A few of these facilities also are located in most other parts of the country (except the Southeast).

Crop-drying procedures vary by type of crop, amount of production, and region. Grain-drying systems are of two major types: (a) high capacity, high temperature, and (b) low temperature. The high temperature systems include batch (both bin and portable) and continuous flow dryers. Continuous flow systems can handle the largest amount of production - over 50,000 bushels annually on the farm, and up to around 3,000 bushels per hour in commercial facilities. Temperatures in continuous flow dryers range up to 121°C (250°F), with average temperatures close to 80°C (176°F). Temperatures in bin and portable batch drying are somewhat lower, between 49° and 66°C (120° to 150°F), and 60° and 93°C (140° to 200°F), respectively. Electricity requirements for fan operation also are high. These systems have the advantage of drying grain quickly, and are used to a large extent in the Midwest, middle-Atlantic states, and Southeast. In the Southeast particularly, it is important to dry grain quickly because of the high humidity, which causes rapid spoilage.

The trend in the Midwest in recent years has been toward lower temperature drying. In-bin drying with temperatures of 27 to 38°C (80° to 100°F) requires more time than high-temperature drying, and must be completed by November before the onset of colder weather and higher humidity. However, energy costs are reduced substantially. The system may be operated with electricity only, in which case a maximum temperature rise of under 3°C (about 5°F) is attained. Other systems enjoying increasing popularity because of their reduced energy requirements are combination drying and dryeration. In the former system, grain initially is dried in a high-temperature system, then slowly cooled and dried with ambient or low-temperature air. The process may take 4 to 6 weeks or longer, and may be discontinued over the winter to be completed the following spring. The dryeration procedure consists of high-temperature drying down to an intermediate (16 to 18 percent) moisture content, after which the grain is "tempered" with low-velocity air circulation.

Rice is most commonly dried in commercial continuous flow dryers with a 21° to 54°C (70° to 130°F) temperature lift. On the farm, peanuts are dried in trailers or bins; in the Southwest most peanut drying takes place in large commercial facilities. Only a low temperature rise - a maximum of about 11°C (20°F) - is used for peanuts.

Tobacco-curing practices vary by type of tobacco. Leaves from flue-cured tobacco, grown in the southeastern and middle Atlantic states, are picked individually as they ripen and dried in conventional or bulk curing barns. In conventional barns the tobacco is hung on sticks and artificial heat (and sometimes artificial ventilation) is supplied. Both artificial heat and ventilation are required in bulk barns, where the tobacco is packed in containers or racks. The temperature is raised in stages up to 77° to 79°C (170° to 175°F), over a period of up to 150 hours. Fired tobacco, grown in Connecticut as well as the Southeast and middle-Atlantic region, requires similar heating, although natural ventilation is most common. Some tobacco is dried naturally without artificial heat or fans.

Alfalfa dehydration is high-temperature drying, with gas temperatures of up to 982°C (1800°F) at the dehy drum entrance. The temperature of the product leaving the dryer is about 77°C (170°F).

To supply the heat required in crop dryers, including curing barns and dehy drums, the fossil fuels of natural gas, LPG, and fuel oil are used. On-farm grain dryers predominantly use LPG, while commercial systems more frequently use natural gas. Commercial rice facilities are designed to burn natural gas, LPG, fuel oil or some combination of fuels. LPG is typically used in southesstern peanut driyers and in on-farm peanut drying in the Southwest; the commercial facilities burn natural gas. LPG and fuel oil are used in tobacco curing. Alfalfa dehy facilities may use natural gas, fuel oil, or even coal or wood fuels, although natural gas is the most common. Some of these dryers are equipped with dual fuel oil and gas burners. Electricity is required for the operation of fans in dryers and tobacco barns, and motors in dehy drums.

Use of wind as an energy source is most feasible in the midwestern states from Indiana west to Colorado, including states as far north and west as Montana and part of Idaho, and as far southwest as New Mexico. The area encompassing the Texas Panhandle, northwestern Oklahoma, and southwestern Kansas is a particularly good region for winds. Nevertheless, use of wind energy for crop drying even in these areas will be restricted by the seasonal mismatch: most crop drying occurs in the fall, whereas wind availability usually is best in winter and spring. The more eastern states of Delaware, Ohio, Maryland, and Pennsylvania do not have as much wind potential as the midwestern and western regions. Good winds occur in California, but not in the central valleys where most crops are grown. The Southeast is very poor in terms of wind availability.

Even if turbines were installed in regions of high wind power (over 300 W/m^2), the economics currently are not favorable if the systems are operated only for crop drying. With the assumptions used in this report (interest rates of 9 to 10 percent; percent equity of 20 percent and 50 percent on 10 year loans; price escalation for fossil fuels of 35 percent annually for the first 2 years and 8 percent annually for the remaining WECS 20-year lifetime; price escalation for electricity of 20 percent annually for the first 2 years and 4 percent annually thereafter; small wind systems costs projected at the 10,000th unit), dryers would have to be operated over at least 6 months for WECS costs to fall below breakeven costs. If wind power averages 300 W/m^2, WECS for dryers operating only for a 6-week period would have a projected-to-breakeven-cost ratio of between 4 and over 15. If wind power averages only 100 W/m^2, this ratio ranges from around 7 to 20. In addition, payback periods are fairly long with the breakeven costs estimated, extending to between 9 and 12 years.

If WECS are used to supply electricity for other farm uses in addition to crop drying, their installation seems economically viable (given the assumptions enumerated above). Because of the intermittent nature of the wind and the expense of long-term storage systems, they probably should be operated as supplemental energy sources, with conventional fuels and electricity retained as back-up. Conventionally supplied electricity will be more economically replaced by WECS than fossil fuels, since it is more expensive on a heat-equivalent basis. In crop-drying applications, WECS thus should find the greatest use in low-temperature drying of grains and peanuts, where the dryers operate over relatively long periods of time and require substantial electricity but relatively little heat. If coupled with a heat pump, the supply of supplemental heat by wind systems also should be economically attractive.

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APPENDIX A
WIND DATA

Table A-1. NUMBER OF STATIONS WITH SUITABLE WIND DATA, BY STATE

State	Stations	State	Stations
Alabama	10	Montana	14
Arizona	14	Nebraska	13
Arkansas	7	Nevada	16
California	65	New Hampshire	3
Colorado	11	New Jersey	7
Connecticut	3	New Mexico	18
Delaware	3	New York	26
Washington, D.C.	4	North Carolina	15
Florida	27	North Dakota	7
Georgia	15	Ohio	12
Hawaii	9	Oklahoma	11
Idaho	8	Oregon	21
Illinois	13	Pennsylvania	19
Indiana	12	Rhode Island	2
Iowa	9	South Carolina	10
Kansas	13	South Dakota	8
Kentucky	8	Tennessee	9
Louisiana	9	Texas	49
Maine	5	Utah	11
Maryland	5	Vermont	2
Massachusetts	9	Virginia	9
Michigan	22	Washington	20
Minnesota	9	West Virginia	3
Mississippi	5	Wisconsin	8
Missouri	14	Wyoming	8
Total			630

Table A-2. RANGES OF AVERAGE ANNUAL WIND SPEEDS AND PEAK AVERAGE WIND SPEEDS, BY STATE

	Wind Speeds (Meters per second)[a]			
	Average Annual[b]		Average Annual[c]	
State	Low	High	Low	High
Alabama	2.4	3.7	3.2	4.8
Arizona	2.1	4.6	2.7	5.5
Arkansas	3.0	4.0	3.9	4.7
California	1.5	6.7	1.7	9.3
Colorado	2.1	6.0	3.1	6.9
Connecticut	4.0	5.4	4.7	6.8
Delaware	4.0	6.5	5.1	7.6
Florida	2.7	4.9	3.3	5.3
Georgia	1.9	4.4	2.3	5.3
Hawaii	2.9	6.3	4.0	7.5
Idaho	3.8	5.0	4.5	5.9
Illinois	3.7	5.5	4.9	6.5
Indiana	3.6	5.5	4.6	6.3
Iowa	4.4	5.8	5.3	7.3
Kansas	3.2	6.7	4.1	7.8
Kentucky	2.3	4.6	3.3	5.4
Louisiana	2.3	4.3	3.2	5.0
Maine	3.5	4.4	4.1	5.1
Maryland	2.3	4.9	3.1	5.0
Massachusetts	2.8	8.8	3.6	10.4
Michigan	3.0	5.6	3.9	7.0
Minnesota	3.4	5.5	4.0	6.3
Mississippi	1.8	3.5	2.7	4.2
Missouri	3.1	5.4	4.0	6.4
Montana	2.5	6.9	3.2	9.3
Nebraska	3.9	6.2	5.0	7.0
Nevada	2.4	4.5	3.1	5.5
New Hampshire	2.5	3.4	3.1	4.3
New Jersey	3.1	4.7	3.9	5.6
New Mexico	2.9	6.7	3.6	7.5
New York	2.9	6.4	3.7	7.6
North Carolina	2.2	5.4	5.4	6.1
North Dakota	4.2	6.7	4.9	7.4
Ohio	3.2	5.5	4.1	6.5
Oklahoma	4.1	6.4	5.1	7.4
Oregon	1.3	6.8	2.0	7.9
Pennsylvania	2.8	6.9	3.7	8.1
Rhode Island	4.3	4.9	4.9	5.5
South Carolina	2.5	4.2	3.3	5.0
South Dakota	4.2	5.8	5.5	7.0
Tennessee	2.7	4.1	3.6	5.1
Texas	3.0	8.1	4.2	9.1
Utah	2.0	5.2	2.8	5.8
Vermont	3.7	4.0	4.4	4.5
Virginia	1.9	4.5	2.7	5.2
Washington	2.0	6.7	2.4	8.6
West Virginia	2.9	3.0	3.6	4.0
Wisconsin	2.9	4.5	3.3	6.0
Wyoming	3.8	7.2	3.4	8.9

[a]Height at which wind speeds were measured varies, but is below 20 meters.
[b]Reading at station with the lowest average annual wind speed, and at station with highest average annual wind speed.
[c]Average reading during peak month, for station with lowest and station with highest reading.

Table A-3. PERCENT OF TOTAL AREA THAT WILL SUPPORT WIND TURBINES AT 10, 20, AND 50 METERS, BY STATE[a]

State	Percent of Area			
	10m	20m	50m	None
Alabama	5	10	40	45
Arizona	25	35	35	5
Arkansas	2	42	56	—
California	25	30	25	20
Colorado	55	15	20	10
Connecticut	35	50	15	—
Delaware	60	40	—	—
Florida	7	48	30	15
Georgia	—	10	45	45
Hawaii	12	38	50	—
Idaho	50	35	14	1
Illinois	85	10	5	—
Indiana	60	20	15	5
Iowa	100	—	—	—
Kansas	93	5	2	—
Kentucky	—	50	25	25
Louisiana	20	10	25	45
Maine	10	90	—	—
Maryland	30	45	20	5
Massachusetts	60	20	15	5
Michigan	80	15	5	—
Minnesota	80	14	5	1
Mississippi	—	1	74	25
Missouri	70	20	10	—
Montana	70	20	10	—
Nebraska	100	—	—	—
Nevada	35	35	20	10
New Hampshire	—	70	20	10
New Jersey	40	53	5	2
New Mexico	70	20	10	—
New York	30	60	5	5
North Carolina	5	15	65	15
North Dakota	85	15	—	—
Ohio	48	35	15	2
Oklahoma	90	10	—	—
Oregon	15	30	20	35
Pennsylvania	30	40	20	10
Rhode Island	90	10	—	—
South Carolina	—	25	60	15
South Dakota	100	—	—	—
Tennessee	—	10	70	20
Texas	65	30	5	—
Utah	15	35	35	15
Vermont	—	55	30	15
Virginia	5	35	20	40
Washington	15	30	35	20
West Virginia	—	15	55	30
Wisconsin	60	40	—	—
Wyoming	65	20	15	—

[a]Percent of total area that will support turbines at a height of 10 meters also will support them at 20 and 50 meters; the area that will support turbines at 20 meters also will support them at 50 meters. For example, in Alabama 55 percent of the state has winds sufficient at 50 meters to support turbines, but 40 percent of the state has winds sufficient only at this height and not at heights of 10 or 20 meters. Original data are from J. W. Reed, *Wind Power Climatology of the United States—Supplement* (Albuquerque, N.M.: Sandia Laboratories, 1979).

APPENDIX B

STATE ESTIMATES OF GRAIN DRYERS

On-Farm Dryers

The number of crop-drying facilities in Illinois was estimated by Morrison and Shove in a 1978 survey.[5] This survey also estimated the percentage of on-farm drying done by each type dryer. From these estimates, the average number of bushels dried per dryer in each category was calculated. The percentage of corn dried on farm with each type dryer is given for Indiana, Ohio, Wisconsin, Michigan, and Iowa by the Corn Harvesting and Handling Reports published by these states. Total number of bushels dried in the state was calculated for each type dryer, and average amounts of corn per dryer from Illinois were used to obtain approximate numbers of crop dryers in these other states. Calculations for dryer numbers are based on corn only since corn is by far the leading grain dried in these states. Other grains are also dried in these same dryers.

Dryer information for Ohio is from a survey undertaken by Dr. Duvick at Ohio State University (as yet unpublished). Estimates obtained from these data were compared with 1974 estimates made by the Ohio Grain, Feed, and Fertilizer Association. The estimates seem comparable if on-farm drying has been increasing in Ohio as it has in other midwestern states.

To obtain approximate figures for the other midwestern states, except for Missouri, the percent of grain dried by each type dryer was assumed to be the same as that of Iowa (farm sizes and climate of these states is similar to farm size and climate in Iowa). For Missouri, the percent of grain dried by each type of dryer was assumed to be between that of Iowa and that of Illinois (also for reasons of similarity in average farm size and climate). Total amounts of corn dried by each type dryer then was calculated and the average amount of corn per dryer in Illinois again was used to obtain numbers of grain dryers.

Estimates for the eastern, western, and southwestern states are more approximate than those for the midwestern states, as substantially more research on grain drying is carried out in the Midwest. Particularly in the western states, where corn is not a major crop and the humidity is low enough so drying may not always be mandatory, information is very limited. To obtain estimates for these states, the first step was to estimate approximate amounts of corn that are stored on and off farm. It was assumed that the ratio of on-farm to off-farm grain storage capacity (from the Agricultural Stabilization and Conservation Service's 1978 Survey) in each state is approximately the same as the ratio of corn (for grain) actually stored on and off farm. These percentages were applied to production figures to obtain amounts of corn stored on and off farm. Essentially all corn for grain in the eastern states must be dried artificially (unless used immediately), so the estimated amount of corn stored on farm was divided by 20,000 (estimated bushels per drying unit) to obtain on-farm dryer figures for Delaware, Maryland, and Pennsylvania. The 20,000 bushel-per-unit estimate was suggested for Maryland by Dr. Bradley Powers, Maryland State Department of Agriculture.

The same methodology was used for the western states as for Delaware, Maryland, and Pennsylvania. Actual numbers of on-farm dryers may be substantially below or above the estimates in table 22 for several reasons. First, in the western states a lower percentage of corn is likely to be artificially dried than in the East and Midwest (no figures are available). Second, farm sizes are larger, suggesting that there may be fewer, higher capacity dryers than in other regions. Both these factors suggest that the estimates in table 22 are too high. On the other hand, bin drying is more feasible in the arid western regions than in the East, and bin dryers generally are lower capacity dryers. A lot of bin dryers thus possibly would raise the estimates generated here.

Commercial Facilities

The number of commercial facilities by state were estimated based on information on total grain capacity for each state and the total number of elevators in the country (elevator inventories by state do not exist). USDA has estimated 14,680 off-farm facilities in the United States, including country, subterminal, and terminal elevators and facilities maintained by processors.[21] Total capacity by state for the states represented in table 22 are shown in table B-1. The percent of total capacity in any one state was applied to the total number of elevators to obtain an approximate number of elevators in that state. This number then was multiplied by the percent of elevators in that state that have drying facilities. Percentages of elevators with drying facilities used for six midwestern states were:

Illinois	90
Iowa	94
Minnesota	78
Ohio	94
Kansas	65
Nebraska	74
Total average	84

For the remaining midwestern states, the average percent of 84 was used; for the eastern states, 100 percent; and for the western states, plus Texas and Oklahoma, 50 percent.

Estimates for Texas and California include rice facilities. There are 42 rice storage warehouses under the Uniform Rice Storage Agreement in California, and 96 in Texas. These numbers were included in table 22, although the total number of rice facilities (all of which would have drying equipment) would be larger.

Table B-1. TOTAL OFF-FARM GRAIN STORAGE CAPACITY, BY STATE

State	Capacity (000 bu)	State	Capacity (000 bu)
Illinois	787,234	Wisconsin	129,664
Indiana	282,960	Delaware	17,870
Iowa	634,994	Maryland	42,208
Kansas	830,602	Pennsylvania	30,055
Michigan	96,665	California	161,888
Minnesota	367,914	Colorado	93,158
Missouri	210,375	Idaho	71,490
Nebraska	487,926	New Mexico	17,662
Ohio	244,536	Oklahoma	205,009
South Dakota	85,044	Texas	837,775

Source: U.S. Department of Agriculture, Agricultural Stabilization and Conservation Service, *Grain Storage Capacity Survey,* October 1978.

APPENDIX C

SAMPLE PAYBACK PERIOD ANALYSES

Table C-1. PAYBACK PERIOD ANALYSIS: 37,500 BU/YR BATCH-IN-BIN GRAIN-DRYING SYSTEM[a]

	50% Equity, 9% Interest				20% Equity, 10% Interest	
Year	Outlays	Σ Outlays	Savings	Σ Savings	Outlays	Σ Outlays
			Assuming Replacement of Natural Gas			
0	7,015	7,015	0	0	2,806	2,806
1	1,768	8,783	1,368	1,368	2,482	5,288
2	1,768	10,551	1,848	3,216	2,482	7,770
3	1,768	12,319	1,996	5,212	2,482	10,252
4	1,768	14,087	2,156	7,368	2,482	12,734
5	1,768	15,855	2,328	9,696	2,402	15,216
6	1,768	17,623	2,514	12,210	2,482	17,698
7	1,700	10,391	2,715	14,925	2,482	20,180
8	1,768	21,159	2,933	17,858	2,482	22,002
9	1,768	22,927	3,167	21,025	2,482	25,144
10	1,768	24,695	3,421	24,446	2,482	27,626
11*	702	25,397	3,694	28,140	702	28,328
12*	702	26,099	3,990	32,130	702	9,030
13	702	26,801	4,309	36,439	702	29,030
14	702	27,503	4,654	41,093	702	30,434
15	702	28,205	5,026	46,119	702	31,136
16	702	28,907	5,428	51,547	702	31,838
17	702	29,609	5,862	57,409	702	32,540
18	702	30,311	6,331	63,740	702	33,242
19	702	31,013	6,838	70,678	702	33,944
20	702	31,715	7,385	77,963	702	34,646
			Assuming Replacement of High-Priced LPG			
0	19,676	19,676	0	0	7,870	7,870
1	4,959	24,635	3,839	3,839	6,960	14,830
2	4,959	29,594	5,183	9,022	6,960	21,790
3	4,959	34,553	5,598	14,620	6,960	28,750
4	4,959	39,512	6,046	20,666	6,960	35,710
5	4,959	44,471	6,530	27,196	6,960	42,670
6	4,959	49,430	7,054	34,250	6,960	49,630
7	4,959	54,389	7,619	41,869	6,960	56,590
8	4,959	59,348	8,228	50,097	6,960	63,550
9	4,959	64,307	8,886	58,984	6,960	70,510
10	4,959	69,266	9,597	68,581	6,960	77,470
11*	1,968	71,234	10,365	78,946	1,968	79,438
12*	1,968	73,202	11,194	90,141	1,968	81,406
13	1,968	75,170	12,090	102,230	1,968	83,374
14	1,968	77,138	13,057	115,287	1,968	85,342
15	1,968	79,106	14,101	129,389	1,968	87,310
16	1,968	81,074	15,230	144,618	1,968	89,278
17	1,968	83,042	16,448	161,067	1,968	91,246
18	1,968	85,010	17,764	178,831	1,968	93,214
19	1,968	86,978	19,185	198,016	1,968	95,182
20	1,968	88,946	20,720	218,736	1,968	97,150
			Assuming Replacement of Electricity			
0	450	450	0	0	180	180
1	113	563	128	128	159	339
2	113	676	154	282	159	498
3	113	789	160	442	159	657
4	113	902	167	609	159	816
5	113	1,015	174	783	159	975
6	113	1,128	181	964	159	1,134
7	113	1,241	188	1,152	159	1,293
8	113	1,354	196	1,348	159	1,452
9*	113	1,467	204	1,552	159	1,611

Table C-1. PAYBACK PERIOD ANALYSIS: 37,500 BU/YR BATCH-IN-BIN GRAIN-DRYING SYSTEM[a] (Cont'd)

	50% Equity, 9% Interest				20% Equity, 10% Interest	
Year	Outlays	Σ Outlays	Savings	Σ Savings	Outlays	Σ Outlays
			Assuming Replacement of Electricity (Cont'd)			
10	113	1,580	212	1,764	159	1,770
11*	45	1,625	220	1,984	45	1,815
12	45	1,670	229	2,213	45	1,860
13	45	1,715	238	2,451	45	1,905
14	45	1,760	248	2,699	45	1,950
15	45	1,805	258	2,957	45	1,995
16	45	1,850	268	3,225	45	2,040
17	45	1,895	279	3,504	45	2,085
18	45	1,940	290	3,794	45	2,130
19	45	1,985	301	4,095	45	2,175
20	45	2,030	313	4,408	46	2,220

Table C-2. PAYBACK PERIOD ANALYSIS: 2,000 BU/YR IN-STORAGE-LAYER GRAIN-DRYING SYSTEM[a]

	50% Equity, 9% Interest				20% Equity, 10% Interest	
Year	Outlays	Σ Outlays	Savings	Σ Savings	Outlays	Σ Outlays
Assuming Replacement of Natural Gas						
0	277	277	0	0	110	110
1	70	347	54	54	98	208
2	70	417	73	127	98	306
3	70	487	79	206	98	404
4	70	557	85	291	98	502
5	70	627	92	383	98	600
6	70	697	99	482	98	698
7	70	767	107	589	98	796
8	70	837	116	705	98	894
9	70	907	125	830	98	992
10	70	977	135	965	98	1,090
11*	28	1,005	146	1,111	28	1,118
12*	28	1,033	157	1,208	28	1,146
13	28	1,061	170	1,438	28	1,174
14	28	1,089	184	1,622	28	1,202
15	28	1,117	198	1,820	28	1,230
16	28	1,145	214	2,034	28	1,258
17	28	1,173	231	2,265	28	1,286
18	28	1,201	250	2,515	28	1,314
19	28	1,229	270	2,785	28	1,342
20	28	1,257	291	3,076	28	1,370
Assuming Replacement of High-Priced LPG						
0	664	664	0	0	266	266
1	170	834	130	130	234	500
2	170	1,004	175	305	234	734
3	170	1,174	189	494	234	968
4	170	1,344	204	698	234	1,202
5	170	1,514	220	918	234	1,436
6	170	1,684	238	1,156	234	1,670
7	170	1,854	257	1,413	234	1,904
8	170	2,024	278	1,691	234	2,138
9	170	2,194	300	1,991	234	2,372
10	170	2,364	324	2,315	234	2,606
11*	66	2,431	350	2,665	66	2,672
12*	66	2,497	378	3,043	66	2,738
13	66	2,564	408	3,451	66	2,804
14	66	2,630	441	3,892	66	2,870
15	66	2,696	476	4,368	66	2,936
16	66	2,762	514	4,882	66	3,002
17	66	2,828	555	5,437	66	3,068
18	66	2,894	599	6,036	66	3,134
19	66	2,960	647	6,683	66	3,200
20	66	3,026	699	7,382	66	3,266
Assuming Replacement of Electricity						
0	108	108	0	0	43	43
1	28	136	31	31	38	81
2	28	163	37	68	38	119
3	28	191	39	107	38	157
4	28	219	41	148	38	195
5	28	246	42	149	38	233
6	28	274	44	193	38	271
7	28	302	46	239	38	309
8	28	330	47	286	38	347
9	28	357	49	335	38	385

Tablo C-2. PAYBACK PERIOD ANALYSIS: 2,000 BU/YR IN-STORAGE-LAYER GRAIN-DRYING SYSTEM[a] (Cont'd)

Year	50% Equity, 9% Interest				20% Equity, 10% Interest	
	Outlays	Σ Outlays	Savings	Σ Savings	Outlays	Σ Outlays
	Assuming Replacement of Electricity (Cont'd)					
10*	28	385	51	386	38	423
11*	11	396	53	439	11	434
12	11	406	55	494	11	445
13	11	417	58	552	11	456
14	11	428	60	612	11	467
15	11	439	62	674	11	478
16	11	450	65	739	11	489
17	11	461	67	806	11	500
18	11	471	70	876	11	511
19	11	482	73	949	11	522
20	11	493	76	1,026	11	533

[a]Savings and outlays in dollars.

Table C-3. PAYBACK PERIOD ANALYSIS: 3,840 CWT/YR PEANUT-DRYING SYSTEM[a]

Year	50% Equity, 9% Interest Outlays	Σ Outlays	Savings	Σ Savings	20% Equity, 10% Interest Outlays	Σ Outlays
			Assuming Replacement of Natural Gas			
0	1,695	1,695	0	0	678	678
1	434	2,129	331	331	612	1,290
2	434	2,563	447	778	612	1,901
3	434	2,997	482	1,260	612	2,513
4	434	3,431	521	1,781	612	3,124
5	434	3,865	562	2,343	612	3,736
6	434	4,298	607	2,950	612	4,347
7	434	4,732	656	3,606	612	4,959
8	434	5,166	709	4,315	612	5,570
9	434	5,600	765	5,080	612	6,182
10	434	6,034	826	5,906	612	6,793
11*	160	6,204	893	6,799	169	6,963
12*	169	6,373	964	7,763	169	7,132
13	169	6,543	1,041	8,804	169	7,302
14	169	6,712	1,124	9,928	169	7,471
15	169	6,882	1,214	11,142	169	7,641
16	169	7,051	1,311	12,453	169	7,810
17	169	7,221	1,416	13,869	169	7,980
18	169	7,390	1,530	15,399	169	8,149
19	169	7,560	1,652	17,051	169	8,319
20	169	7,729	1,784	18,835	169	8,488
			Assuming Replacement of High-Speed LPG			
0	4,670	4,670	0	0	1,868	1,868
1	1,195	5,865	911	911	1,685	3,553
2	1,195	7,061	1,230	2,141	1,685	5,238
3	1,195	8,256	1,329	3,470	1,685	6,923
4	1,195	9,452	1,435	4,905	1,685	8,607
5	1,195	10,647	1,550	6,455	1,685	10,292
6	1,195	11,843	1,674	8,129	1,685	11,977
7	1,195	13,038	1,808	9,937	1,685	13,662
8	1,195	14,234	1,952	11,889	1,685	15,347
9	1,195	15,429	2,108	13,997	1,685	17,032
10	1,195	16,625	2,277	16,274	1,685	18,717
11*	467	17,092	2,459	18,733	467	19,184
12*	467	17,559	2,656	21,389	467	19,651
13	467	18,026	2,868	24,257	467	20,118
14	467	18,492	3,098	27,355	467	20,585
15	467	18,959	3,346	30,701	467	21,052
16	467	19,426	3,613	34,314	467	21,519
17	467	19,893	3,903	38,217	467	21,986
18	467	20,360	4,215	42,432	407	22,452
19	467	20,827	4,552	46,984	467	22,919
20	467	21,294	4,916	51,900	467	23,386
			Assuming Replacement of Electricity			
0	736	736	0	0	294	294
1	188	924	212	212	266	560
2	188	1,113	255	467	266	825
3	188	1,301	265	732	266	1,091
4	188	1,490	276	1,008	266	1,357
5	188	1,678	287	1,295	266	1,622
6	188	1,866	298	1,593	266	1,888
7	188	2,055	310	1,903	266	2,153
8	188	2,243	323	2,226	266	2,419

Table C-3. PAYBACK PERIOD ANALYSIS: 3,840 CWT/YR PEANUT-DRYING SYSTEM[a] (Cont'd)

	50% Equity, 9% Interest				20% Equity, 10% Interest	
Year	Outlays	Σ Outlays	Savings	Σ Savings	Outlays	Σ Outlays
			Assuming Replacement of Electricity (Cont'd)			
9*	188	2,432	335	2,561	266	2,684
10	188	2,620	349	2,910	266	2,950
11*	74	2,694	363	3,273	74	3,023
12	74	2,767	377	3,650	74	3,097
13	74	2,841	392	4,042	74	3,171
14	74	2,914	408	4,450	74	3,244
15	74	2,988	424	4,874	74	3,318
16	74	3,062	441	5,315	74	3,391
17	74	3,135	459	5,774	74	3,465
18	74	3,209	477	6,251	74	3,539
19	74	3,282	496	6,747	74	3,612
20	74	3,356	516	7,263	74	3,686

[a]Savings and outlays in dollars.

Table C-4. PAYBACK PERIOD ANALYSIS: BULK BARN TOBACCO CURING[a]

Year	50% Equity, 9% Interest				20% Equity, 10% Interest	
	Outlays	Σ Outlays	Savings	Σ Savings	Outlays	Σ Outlays
Assuming Replacement of Fuel Oil						
0	3,528	3,528	0	0	1,411	1,411
1	903	4,432	689	689	1,273	2,684
2	903	5,335	929	1,618	1,273	3,957
3	903	6,238	1,004	2,622	1,273	5,230
4	903	7,141	1,084	3,706	1,273	6,503
5	903	8,045	1,171	4,877	1,273	7,776
6	903	8,948	1,265	6,142	1,273	9,049
7	903	9,851	1,366	7,508	1,273	10,322
8	903	10,754	1,475	8,983	1,273	11,595
9	903	11,658	1,593	10,576	1,273	12,868
10	903	12,561	1,720	12,296	1,273	14,141
11*	353	12,914	1,858	14,154	353	14,494
12*	353	13,266	2,007	16,161	353	14,847
13	353	13,619	2,167	18,328	353	15,200
14	353	13,972	2,341	20,669	353	15,553
15	353	14,325	2,528	23,197	353	15,906
16	353	14,678	2,730	25,927	353	16,258
17	353	15,031	2,948	28,875	353	16,611
18	353	15,383	3,184	32,059	353	16,964
19	353	15,736	3,439	35,498	353	17,317
20	353	16,089	3,714	39,212	353	17,670
Assuming Replacement of Electricity						
0	100	100	0	0	40	40
1	20	120	22	22	30	70
2	20	140	27	49	30	100
3	20	160	28	77	30	130
4	20	180	29	106	30	160
5	20	200	30	136	30	190
6	20	220	31	167	30	220
7	20	240	32	199	30	250
8	20	260	34	233	30	280
9	20	280	35	268	30	310
10*	20	300	36	304	30	340
11	5	305	38	342	5	345
12*	5	310	39	381	5	360
13	5	315	41	422	5	355
14	5	320	43	465	5	360
15	5	325	44	509	5	365
16	5	330	46	555	5	370
17	5	335	48	603	5	375
18	5	340	50	653	5	380
19	5	345	52	705	5	385
20	5	350	54	759	5	390

[a]Savings and outlays in dollars.

Table C-5. PAYBACK PERIOD ANALYSIS: 1,000 TON/YR ALFALFA DEHY OPERATION, ASSUMING REPLACEMENT OF ELECTRICITY[a]

	50% Equity, 9% Interest				20% Equity, 10% Interest	
Year	Outlays	Σ Outlays	Savings	Σ Savings	Outlays	Σ Outlays
0	21,414	21,414	0	0	8,566	8,566
1	5,482	26,896	6,180	6,180	7,726	16,292
2	5,482	32,378	7,416	13,596	7,726	24,018
3	5,482	37,860	7,713	21,309	7,726	31,744
4	5,482	43,342	8,021	29,330	7,726	39,470
5	5,482	48,824	8,342	37,672	7,726	47,196
6	5,482	54,305	8,676	46,348	7,726	54,922
7	5,482	59,787	9,023	55,371	7,726	62,648
8	5,482	65,269	9,384	64,755	7,726	70,374
9*	5,482	70,751	9,759	74,514	7,726	78,101
10	5,482	76,233	10,149	84,663	7,726	85,827
11*	2,141	78,375	10,555	95,218	2,141	87,968
12	2,141	80,516	10,977	106,195	2,141	90,109
13	2,141	82,657	11,417	117,612	2,141	92,251
14	2,141	84,799	11,873	129,485	2,141	94,392
15	2,141	86,940	12,348	141,833	2,141	96,534
16	2,141	89,082	12,842	154,675	2,141	98,675
17	2,141	91,223	13,356	168,031	2,141	100,816
18	2,141	93,364	13,890	181,921	2,141	102,958
19	2,141	95,506	14,446	196,367	2,141	105,099
20	2,141	97,647	15,023	211,390	2,141	107,240

[a]Savings and outlays in dollars.

APPENDIX D

DEVELOPMENTAL SWECS TESTED AT ROCKY FLATS

System	Out @ 20 mph (kW)	Description
ASI Pinson 1 kW	1	Three-bladed, vertical-axis rotor
Northwind 2 kW	2	Three-bladed, horizontal-axis rotor
Enertech 2 kW	2	Two-bladed, horizontal-axis rotor
UTRC 8 kW	9	Two-bladed, horizontal-axis rotor
Grumman 8 kW	11	Three-bladed, horizontal-axis rotor
Windworks 8 kW	8	Three-bladed, horizontal-axis rotor
Kaman 40 kW	40	Two-bladed, horizontal-axis rotor
McDonnell 40 kW	40	Three-bladed, vertical-axis rotor

Source: Rockwell International Corporation, Wind Systems Program, Rocky Flats Plant, Energy Systems Group, "System Summary of Small Wind Energy Conversion Systems (SWECS) Development," 1979.

APPENDIX E

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★ U.S. GOVERNMENT PRINTING OFFICE: 1981— 771-039/358