MASTER

Solar-Climatic Statistical Study

Summary Report
Volume 1 of 2

February 1979

Prepared for:
U.S. Department of Energy
Assistant Secretary for Energy Technology
Office of Solar, Geothermal, Electric
and Storage Systems

Under Contract No. EG-77-C-01-4016

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February 1979

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U.S. Department of Energy
Assistant Secretary for Energy Technology
Office of Solar, Geothermal, Electric
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Washington, D.C. 20545
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FOREWORD

This technical report presents work performed by Northrop Services, Inc., Huntsville, Alabama, while under contract (EG-77-C-01-4016) to the United States Department of Energy (DOE). The DOE Project Manager for the study was Mr. Michael R. Riches, Division of Planning and Technology Transfer (ETS), Environmental Planning and Analysis Branch. Technical coordination was provided by the Sandia Laboratories.

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Roger E. Bray
Principal Investigator

ABSTRACT

Design and operation of large scale solar and wind energy conversion systems should be based, in part, on knowledge of expected solar and wind power trends. For this purpose, historic data at 26 (SOLMET) National Weather Service stations were processed to provide preliminary planning data, in the form of statistical information, for selected daily average solar and wind conditions occurring and persisting for time periods of interest. Solar data are global radiation incident on a horizontal surface, and wind data represent wind power normal to the air flow. Empirical probabilities were constructed from the historic solar and wind data to provide a reasonable inference of the chance of similar climatological conditions occurring at any given time in the future. (Diurnal wind power variations were also considered.) These data are presented in Volume II, and comprehensive plots for all stations are provided on a set of microfiche, contained in a folder in the back of Volume II.

Data used to obtain the daily average solar and wind power probabilities were combined into monthly averages and are presented in this volume as summary results. Average monthly, seasonal and annual solar and wind power trends were prepared to provide an overview for identifying areas for further investigation. Documentation of the program (METPRO) developed to accomplish the overall study is included in the appendices of Volume II.

TABLE OF CONTENTS - VOLUME I

<u>Section</u>	<u>Title</u>	<u>Page</u>
	FOREWORD.	ii
	ACKNOWLEDGMENT.	ii
	ABSTRACT.	iii
	LIST OF FIGURES	vi
I	INTRODUCTION.	1-1
II	GENERAL SUMMARY	2-1
	2.1 STUDY SCOPE AND OBJECTIVE.	2-1
	2.2 GUIDELINES AND APPROACH.	2-3
III	INSOLATION AND WIND POWER MONTHLY SUMMARIES	3-1
IV	REFERENCES.	4-1

TABLE OF CONTENTS - VOLUME II

<u>Section</u>	<u>Title</u>	<u>Page</u>
	FOREWORD.	ii
	ACKNOWLEDGMENT	ii
	ABSTRACT.	iii
	LIST OF FIGURES	v
I	INTRODUCTION.	1-1
II	TECHNICAL APPROACH.	2-1
	2.1 METHODOLOGY.	2-1
	2.2 DATA REQUIREMENTS.	2-3
	2.3 STATISTICAL TECHNIQUES	2-7
III	INSOLATION AND WIND POWER STATISTICS.	3-1
	3.1 DISCUSSION OF FIGURES AND TABLES	3-3
	3.2 SUCCESSIVE DAY PROBABILITIES	3-8
	3.3 PROBABILITIES OF PERSISTENCE	3-8
	3.4 JOINT PROBABILITIES.	3-8
	3.5 SUMMARY.	3-9
IV	REFERENCES.	4-1
	Appendix A - COMPREHENSIVE STATISTICAL RESULTS - SAMPLE	A-1
	Appendix B - TABLES - SUCCESSIVE DAY AND PERSISTENCE PROBABILITIES.	B-1
	Appendix C - SELECTED SOLAR AND WIND PLOTS.	C-1
	C.1 SUCCESSIVE DAY PROBABILITIES	C-7
	C.2 PROBABILITIES OF PERSISTENCE	C-111
	C.3 JOINT PROBABILITIES.	C-163
	Appendix D - PROGRAM METPRO	D-1
	D.1 GENERAL.	D-1
	D.2 METPRO1.	D-2
	D.3 METPRO2.	D-7
	Appendix E - PROGRAM LISTING.	E-1
	E.1 METPRO1 LISTING.	E-3
	E.2 METPRO2 LISTING.	E-13

LIST OF FIGURES

<u>Figure</u>	<u>Title</u>	<u>Page</u>
2-1	SOLMET HOURLY REPORTING STATIONS.	2-2
3-1	DAILY AVERAGE WIND POWER VS. DAILY AVERAGE WIND SPEED	3-2
3-2	AVAILABLE SOLAR AND WIND POWER - JANUARY	3-3
3-3	AVAILABLE SOLAR AND WIND POWER - FEBRUARY	3-4
3-4	AVAILABLE SOLAR AND WIND POWER - MARCH.	3-5
3-5	AVAILABLE SOLAR AND WIND POWER - APRIL.	3-6
3-6	AVAILABLE SOLAR AND WIND POWER - MAY.	3-7
3-7	AVAILABLE SOLAR AND WIND POWER - JUNE	3-8
3-8	AVAILABLE SOLAR AND WIND POWER - JULY	3-9
3-9	AVAILABLE SOLAR AND WIND POWER - AUGUST	3-10
3-10	AVAILABLE SOLAR AND WIND POWER - SEPTEMBER.	3-11
3-11	AVAILABLE SOLAR AND WIND POWER - OCTOBER.	3-12
3-12	AVAILABLE SOLAR AND WIND POWER - NOVEMBER	3-13
3-13	AVAILABLE SOLAR AND WIND POWER - DECEMBER	3-14
3-14	DAILY AVERAGE INSOLATION AND WIND POWER, BY MONTH AND ANNUAL - ALBUQUERQUE, NM	3-16
3-15	DAILY AVERAGE INSOLATION AND WIND POWER, BY MONTH AND ANNUAL - APALACHICOLA, FL.	3-17
3-16	DAILY AVERAGE INSOLATION AND WIND POWER, BY MONTH AND ANNUAL - BISMARCK, ND.	3-18
3-17	DAILY AVERAGE INSOLATION AND WIND POWER, BY MONTH AND ANNUAL - BOSTON, MA	3-19
3-18	DAILY AVERAGE INSOLATION AND WIND POWER, BY MONTH AND ANNUAL - BROWNSVILLE, TX	3-20
3-19	DAILY AVERAGE INSOLATION AND WIND POWER, BY MONTH AND ANNUAL - CAPE HATTERAS, NC	3-21
3-20	DAILY AVERAGE INSOLATION AND WIND POWER, BY MONTH AND ANNUAL - CARIBOU, ME	3-22
3-21	DAILY AVERAGE INSOLATION AND WIND POWER, BY MONTH AND ANNUAL - CHARLESTON, SC.	3-23
3-22	DAILY AVERAGE INSOLATION AND WIND POWER, BY MONTH AND ANNUAL - COLUMBIA, MO	3-24

LIST OF FIGURES (Concluded)

<u>Figure</u>	<u>Title</u>	<u>Page</u>
3-23	DAILY AVERAGE INSOLATION AND WIND POWER, BY MONTH AND ANNUAL - DODGE CITY, KS.	3-25
3-24	DAILY AVERAGE INSOLATION AND WIND POWER, BY MONTH AND ANNUAL - EL PASO, TX	3-26
3-25	DAILY AVERAGE INSOLATION AND WIND POWER, BY MONTH AND ANNUAL - ELY, NV	3-27
3-26	DAILY AVERAGE INSOLATION AND WIND POWER, BY MONTH AND ANNUAL - FORT WORTH, TX.	3-28
3-27	DAILY AVERAGE INSOLATION AND WIND POWER, BY MONTH AND ANNUAL - FRESNO, CA.	3-29
3-28	DAILY AVERAGE INSOLATION AND WIND POWER, BY MONTH AND ANNUAL - GREAT FALLS, MT	3-30
3-29	DAILY AVERAGE INSOLATION AND WIND POWER, BY MONTH AND ANNUAL - LAKE CHARLES, I.A.	3-31
3-30	DAILY AVERAGE INSOLATION AND WIND POWER, BY MONTH AND ANNUAL - MADISON, WI	3-32
3-31	DAILY AVERAGE INSOLATION AND WIND POWER, BY MONTH AND ANNUAL - MEDFORD, OR	3-33
3-32	DAILY AVERAGE INSOLATION AND WIND POWER, BY MONTH AND ANNUAL - MIAMI, FL	3-34
3-33	DAILY AVERAGE INSOLATION AND WIND POWER, BY MONTH AND ANNUAL - NASHVILLE, TN	3-35
3-34	DAILY AVERAGE INSOLATION AND WIND POWER, BY MONTH AND ANNUAL - NEW YORK, NY	3-36
3-35	DAILY AVERAGE INSOLATION AND WIND POWER, BY MONTH AND ANNUAL - NORTH OMAHA, NB	3-37
3-36	DAILY AVERAGE INSOLATION AND WIND POWER, BY MONTH AND ANNUAL - PHOENIX, AZ	3-38
3-37	DAILY AVERAGE INSOLATION AND WIND POWER, BY MONTH AND ANNUAL - SANTA MARIA, CA	3-39
3-38	DAILY AVERAGE INSOLATION AND WIND POWER, BY MONTH AND ANNUAL - SEATTLE-TACOMA, WA	3-40
3-39	DAILY AVERAGE INSOLATION AND WIND POWER, BY MONTH AND ANNUAL - WASHINGTON, DC-STERLING, VA	3-41

Section I

INTRODUCTION

National assessments are being made to find suitable test and evaluation locations for large scale solar and wind energy conversion systems. Design and operation of such systems, as well as site selection, should be based on knowledge of expected solar insolation and wind power trends at the locations. Thus, Northrop Services, Inc., performed a study to provide preliminary planning data, in the form of statistical information, for selected solar and wind conditions occurring and persisting for periods of time at selected sites. The sites are 26 (SOLMET) National Weather Service stations (ref. 10) measuring hourly insolation and collateral meteorological data. The data base for this study is the historical data that go back nearly 24 years for each station. The data are available from the National Climatic Center.

Solar and wind energy available at the specific locations are compared by expressing these forms of energy in the same units of watts/square meter. Solar energy is the global radiation incident on a horizontal surface and wind energy is the wind power perpendicular to the air flow.

Empirical probabilities are constructed from the historical data to provide estimates of daily average insolation and wind power, independently and in combination, occurring and persisting at or above specified thresholds for up to one week. Diurnal wind power variations are also considered. (These data are presented in Volume II, along with the technical approach followed to accomplish the study.) Summary results have been prepared by combining into monthly averages the solar and wind values used in obtaining the above probabilities. Daily values were averaged over a month to obtain a monthly average value of insolation and wind power. These monthly averages were then averaged over the years of record to obtain average monthly values for insolation and wind power. Data were combined to show seasonal and annual trends, in addition to the monthly trends.

Presented in Section II is a general summary of the study objectives and approach. Summary results assembled, as described above, for an overview of monthly, seasonal and yearly averages of insolation and wind power are presented in Section III. The program, METPRO, developed to accomplish the overall Solar-Climatic Statistical Study has been documented in Volume II. Program variable definitions, subroutine abstracts, flow charts and program listings provide the prospective user inclusive information for setting up and running program METPRO.

Section II

GENERAL SUMMARY

The primary purpose of this study is to provide preliminary planning data to aid in assessing the feasibility of solar, wind, or hybrid solar-wind energy systems at or near 26 sites in the United States. Historic data at the 26 sites are available through the National Climatic Center (NCC) on magnetic tape for periods of up to 24 years. Hourly solar insolation and collateral meteorological data are recorded in a common tape format, SOLMET, and the 26 stations are referred to as the SOLMET stations. (Shown in Figure 2-1 are the relative locations of each station throughout the contiguous United States).

Global solar radiation and wind speed data taken from the SOLMET tapes are used to derive empirical probabilities for daily average insolation and wind power occurring and persisting, at or above specified levels, or thresholds, over time periods of interest. This study is based on previous work by Carter (ref. 3) and Graves (ref. 6) in determining frequencies of occurrence of weather events. As in those studies, the term probability is also used here to mean the straightforward empirical probability obtained using the frequencies of occurrence of climatological variables at or above stated criteria.

2.1 STUDY SCOPE AND OBJECTIVE

The objective of the study was to provide probability estimates of insolation and wind power, alone and in combination, occurring and persisting at or above specified thresholds for up to one week. Basically, empirical probabilities were obtained for:

- average daily insolation and average daily wind power, independently, equaling or exceeding five thresholds, on a monthly basis, for successive occurrences of up to one week,
- persistence, for up to one week, of insolation and wind power, independently, at or above five thresholds, on a monthly basis, and
- the (successive) occurrence and persistence of joint combinations of insolation and wind power equaling or exceeding all permutations of three thresholds each, also for periods of up to one week.

Figure 2-1. SOLMET HOURLY REPORTING STATIONS

Note that diurnal wind power probabilities were also obtained. In addition to the above results, monthly averages of insolation and wind power were also obtained.

Presented in this volume are summary results - daily average values of insolation and wind power, by month. The statistical data are presented in Volume II.

2.2 GUIDELINES AND APPROACH

Statistical data derived from the study are obtained, essentially, by counting the number of occurrences of a specified condition being satisfied and dividing by the total number of trials. Empirical probabilities are constructed, by month, for daily average values of insolation and wind power, independently, equaling or exceeding each of several thresholds for 1, 2, ..., and 14 successive days. These are unconditional probabilities obtained from numbers of occurrences in given sample sizes. Using these probabilities, conditional probabilities are constructed (as discussed in the Technical Approach, Volume II) for events persisting at or above each of several thresholds for 2, ..., and 14 days. Persistence is defined as an event continuing at or above a threshold for a certain number of days, once it has occurred at or above that threshold. For example, 2-day persistence is defined to mean an event continues to occur for the next day in sequence after it has occurred the first day.

The meteorological parameters considered in this study were solar radiation and wind power. Comparisons of the amounts of solar and wind energy available at specific locations can be made by expressing these forms of energy in the same units. Simple calculations allow the basic comparison of the energy per unit area of wind perpendicular to the air flow and of solar radiation on a unit area of horizontal surface.

Insolation values were taken from the Standard Year Corrected field on the SOLMET set of data tapes since this field contains the rehabilitated serially complete solar radiation data. These data are global radiation data incident on a horizontal surface based on a solar constant of $1377 \text{ Joules}/(\text{m}^2 \cdot \text{s})$; that

is, total direct and diffuse radiation coming from all parts of the sky. Hourly insolation data are summed for the day, converted to watts/m^2 , and divided by 24 (or by 8 if data was recorded every third hour) to obtain a daily average value. This is consistent with data published in climatic atlases of the United States by the NCC.

Wind power data are calculated from wind speed summarized records. The amount of wind power contained in the wind can be expressed as one-half the air density times the cube of the wind speed. Obviously, all the energy cannot be extracted from the wind since the airflow would stop. At best, windmill theory (ref. 1) shows that a maximum of 59.3% of the power contained in the wind can be extracted as useful kinetic energy. In this study, power contained in the wind is treated as a meteorological parameter and the problems of recovery, efficiency, etc., are left to the engineer. Wind power is calculated at each hourly observation in units of watts/m^2 , summed for the day, and analogous to insolation, divided by the total number of daily observations to obtain a daily average value. Diurnal wind power variations are obtained in the same manner, where the basis is the total day. Note that recorded surface wind speed anemometer data have been adjusted to a "common" 10 meter height above the local terrain using the one-seventh power law, which is reasonable for the typically airport environment for the SOLMET data. One should also note that, in calculating wind power, wind speeds below 1.6 m/s were considered to produce no wind power and wind speeds above 14.2 m/s were set to 14.2 m/s to eliminate biasing daily averages when unusually high or gusty winds were observed.

Section III

INSOLATION AND WIND POWER MONTHLY SUMMARIES

Summary results were obtained for monthly average values of insolation and wind power. These values were essentially by-products of the statistical portion of the study and were assembled for a quick-look at comparative (or diverse) solar and wind conditions at the various SOLMET stations. Daily average values of insolation and wind power, for a particular month, were averaged over that month to obtain, essentially, the "average" daily average value for the month. Monthly averages were then averaged over the 20 years or so of records at each station to obtain average values for each month. These data were then combined in several different forms, as will be presented as follows, for an informative or comparative overview of average monthly solar and wind data.

Daily wind speed averages are not readily obtainable from daily average wind power due to the hourly variability. An estimate, however, of the daily average wind speed that would correspond, or relate, to the wind power presented, has been provided. Daily average wind speed associated with each wind power calculation was recorded for all years of data at several stations. By taking the mean of the distribution of daily average winds speeds at several power levels, a first order representation of wind speed to wind power can be obtained, as shown in Figure 3-1.

Solar energy on a horizontal surface generally increases from the northerly to the southerly latitudes, and varies from a peak in the summer months to lows in the winter months. (These variations are not as pronounced for a tilted surface.) Wind power, on the other hand, is quite variable, with the coastal regions affected by local exposure. Wind power is usually highest in the spring, and lower in summer than in fall and winter.

Monthly average values of daily average solar insolation and wind power were obtained for each of the SOLMET stations. (Note that daily average totals can be obtained by multiplying by 24.) Presented in Figures 3-2 through 3-13 are maps of the United States showing the available solar and wind power at

Figure 3-1. DAILY AVERAGE WIND POWER VS. DAILY AVERAGE WIND SPEED

Figure 3-2. AVAILABLE SOLAR AND WIND POWER — JANUARY

Figure 3-3. AVAILABLE SOLAR AND WIND POWER - FEBRUARY

Figure 3-4. AVAILABLE SOLAR AND WIND POWER — MARCH

Figure 3-5. AVAILABLE SOLAR AND WIND POWER - APRIL

Figure 3-6. AVAILABLE SOLAR AND WIND POWER — MAY

Figure 3-7. AVAILABLE SOLAR AND WIND POWER — JUNE

3-9

Figure 3-8. AVAILABLE SOLAR AND WIND POWER - JULY

Figure 3-9. AVAILABLE SOLAR AND WIND POWER — AUGUST

Figure 3-10. AVAILABLE SOLAR AND WIND POWER - SEPTEMBER

Figure 3-11. AVAILABLE SOLAR AND WIND POWER — OCTOBER

Figure 3-12. AVAILABLE SOLAR AND WIND POWER — NOVEMBER

Figure 3-13. AVAILABLE SOLAR AND WIND POWER — DECEMBER

each site, by month. (One must be reminded that the term available refers to the power contained in the wind, as discussed in Section II.) The lower number (in italics) at each site represents the calculated daily average wind power for that month, while the upper number is insolation. The data points, for this study, are too scattered to present meaningful iso-lines. However, one can still visualize the interstation variability.

It is of interest to look at the same information, with the addition of diurnal variations of wind, as a function of the months of the year, for each station. These data, together with the sum of insolation and wind power to indicate total available combined energy, are presented in Figures 3-14 through 3-39. Specifically, daily average values are presented by month and annual for insolation, wind power (day), wind power (night), wind power (total day) and the sum of insolation plus wind power (total). These data are presented for each SOLMET station in alphabetic order. The month Roman numeral code is as follows: I is January, ..., XII = December and XIII = annual average. Note, for the diurnal wind power variations, that at most sites daytime wind power has the greater annual average. At several of these locations, however, it can be seen that nighttime wind averages are higher in the winter months. Energy demand curves can be superimposed over the combined, or total, energy curves to aid in identifying areas that warrant further investigation for possible hybrid energy applications.

The data were also combined in seasonal form for considerations of annual variability of available power that could possibly be applied to electricity demands. Daily averages were prepared for insolation and wind power, along with diurnal wind power variations, by season and annual. These data are presented in Table 3-1 for each station in alphabetic order. The heading codes used are WI-winter, SP-spring, SU-summer, FA-fall and AN-annual average. Other codes are self-explanatory.

Figure 3-14. DAILY AVERAGE INSOLATION AND WIND POWER, BY MONTH AND ANNUAL - ALBUQUERQUE, NM

Figure 3-15. DAILY AVERAGE INSOLATION AND WIND POWER, BY MONTH AND ANNUAL — APALACHICOLA, FL

Figure 3-16. DAILY AVERAGE INSOLATION AND WIND POWER, BY MONTH AND ANNUAL — BISMARCK, ND

Figure 3-17. DAILY AVERAGE INSOLATION AND WIND POWER, BY MONTH AND ANNUAL — BOSTON, MA

Figure 3-18. DAILY AVERAGE INSOLATION AND WIND POWER, BY MONTH AND ANNUAL — BROWNSVILLE, TX

Figure 3-19. DAILY AVERAGE INSOLATION AND WIND POWER, BY MONTH AND ANNUAL — CAPE HATTERAS, NC

Figure 3-20. DAILY AVERAGE INSOLATION AND WIND POWER, BY MONTH AND ANNUAL - CARIBOU, ME

Figure 3-21. DAILY AVERAGE INSOLATION AND WIND POWER, BY MONTH AND ANNUAL — CHARLESTON, SC

Figure 3-22. DAILY AVERAGE INSOLATION AND WIND POWER, BY MONTH AND ANNUAL -- COLUMBIA, MO

Figure 3-23. DAILY AVERAGE INSOLATION AND WIND POWER, BY MONTH AND ANNUAL — DODGE CITY, KS

Figure 3-24. DAILY AVERAGE INSOLATION AND WIND POWER, BY MONTH AND ANNUAL — EL PASO, TX

Figure 3-25. DAILY AVERAGE INSOLATION AND WIND POWER, BY MONTH AND ANNUAL — ELY, NV

Figure 3-26. DAILY AVERAGE INSOLATION AND WIND POWER, BY MONTH AND ANNUAL — FORT WORTH, TX

Figure 3-27. DAILY AVERAGE INSOLATION AND WIND POWER, BY MONTH AND ANNUAL — FRESNO, CA

Figure 3-28. DAILY AVERAGE INSOLATION AND WIND POWER, BY MONTH AND ANNUAL — GREAT FALLS, MT

Figure 3-29. DAILY AVERAGE INSOLATION AND WIND POWER, BY MONTH AND ANNUAL — LAKE CHARLES, LA.

Figure 3-30. DAILY AVERAGE INSOLATION AND WIND POWER, BY MONTH AND ANNUAL — MADISON, WI

Figure 3-31. DAILY AVERAGE INSOLATION AND WIND POWER, BY MONTH AND ANNUAL — MEDFORD, OR

Figure 3-32. DAILY AVERAGE INSOLATION AND WIND POWER, BY MONTH AND ANNUAL — MIAMI, FL

Figure 3-33. DAILY AVERAGE INSOLATION AND WIND POWER, BY MONTH AND ANNUAL — NASHVILLE, TN

Figure 3-34. DAILY AVERAGE INSOLATION AND WIND POWER, BY MONTH AND ANNUAL —, NEW YORK, NY

Figure 3-35. DAILY AVERAGE INSOLATION AND WIND POWER, BY MONTH AND ANNUAL — NORTH OMAHA, NB

Figure 3-36. DAILY AVERAGE INSOLATION AND WIND POWER, BY MONTH AND ANNUAL — PHOENIX, AZ

Figure 3-37. DAILY AVERAGE INSOLATION AND WIND POWER, BY MONTH AND ANNUAL — SANTA MARIA, CA

Figure 3-38. DAILY AVERAGE INSOLATION AND WIND POWER, BY MONTH AND ANNUAL — SEATTLE-TACOMA, WA

Figure 3-39. DAILY AVERAGE INSOLATION AND WIND POWER, BY MONTH AND ANNUAL — WASHINGTON, D.C.-STERLING, VA

Table 3-1. DAILY AVERAGE INSOLATION AND WIND POWER (Watts/M²)
SEASONAL AND ANNUAL

Albuquerque, NM

	WI	SP	SU	FA	AN
Insol.	138	282	332	199	236
Wind (D)	30	75	36	30	43
Wind (N)	39	44	38	37	40
Wind (T)	69	119	74	67	83

Charleston, SC

	WI	SP	SU	FA	AN
Insol.	104	213	228	151	174
Wind (D)	53	68	41	38	50
Wind (N)	44	33	11	24	28
Wind (T)	97	101	52	62	78

Apalachicola, FL

Insol.	119	230	235	170	188
Wind (D)	47	59	32	31	42
Wind (N)	46	33	11	24	28
Wind (T)	93	92	43	55	70

Columbia, MO

Insol.	85	198	264	139	172
Wind (D)	58	76	32	41	52
Wind (N)	64	50	13	38	42
Wind (T)	122	126	45	79	94

Bismarck, ND

Insol.	65	190	263	118	159
Wind (D)	53	130	83	85	88
Wind (N)	90	53	29	61	59
Wind (T)	143	183	112	146	147

Dodge City, KS

Insol.	110	232	289	165	199
Wind (D)	89	165	113	105	118
Wind (N)	121	110	60	88	95
Wind (T)	210	275	173	193	213

Boston, MA

Insol.	66	172	218	112	142
Wind (D)	102	135	74	79	98
Wind (N)	183	107	42	93	107
Wind (T)	285	242	116	172	205

El Paso, TX

Insol.	152	297	290	208	245
Wind (D)	40	74	30	25	43
Wind (N)	55	66	31	30	42
Wind (T)	95	140	61	55	85

Brownsville, TX

Insol.	123	221	274	181	200
Wind (D)	91	157	110	73	108
Wind (N)	63	64	27	32	47
Wind (T)	154	221	137	105	155

Ely, NV

Insol.	112	254	311	182	215
Wind (D)	34	73	57	42	52
Wind (N)	70	43	28	44	46
Wind (T)	104	116	85	86	98

Cape Hatteras, NC

Insol.	97	219	244	150	192
Wind (D)	73	84	58	65	70
Wind (N)	116	77	44	76	78
Wind (T)	189	161	102	141	148

Fort Worth, TX

Insol.	111	213	272	165	190
Wind (D)	68	99	51	51	67
Wind (N)	69	57	25	38	48
Wind (T)	137	156	76	89	115

Caribou, ME

Insol.	61	176	217	91	136
Wind (D)	83	118	77	71	87
Wind (N)	125	79	22	65	73
Wind (T)	208	197	99	136	160

Fresno, CA

Insol.	95	265	339	183	221
Wind (D)	11	23	15	8	14
Wind (N)	11	22	20	10	16
Wind (T)	22	45	35	18	30

Table 3-1. DAILY AVERAGE INSOLATION AND WIND POWER (Watts/M²)
SEASONAL AND ANNUAL (Concluded)

Great Falls, MT

	WI	SP	SU	FA	AN
Insol.	62	194	276	119	163
Wind (D)	118	120	72	110	105
Wind (N)	200	63	31	101	89
Wind (T)	318	183	103	211	194

Lake Charles, LA

Insol.	103	205	235	158	175
Wind (D)	55	72	28	37	48
Wind (N)	50	44	7	25	32
Wind (T)	105	116	35	62	80

Madison, WI

Insol.	72	184	243	115	154
Wind (D)	51	88	50	55	61
Wind (N)	70	53	13	45	45
Wind (T)	121	141	63	100	106

Medford, OR

Insol.	63	207	298	131	175
Wind (D)	12	22	22	9	17
Wind (N)	14	11	5	8	10
Wind (T)	26	33	27	17	27

Miami, FL

Insol.	143	229	221	168	190
Wind (D)	54	66	37	49	52
Wind (N)	33	33	14	27	27
Wind (T)	87	99	51	76	79

Nashville, TN

Insol.	82	193	242	138	164
Wind (D)	39	50	21	26	34
Wind (N)	45	32	8	20	26
Wind (T)	84	82	29	46	60

New York, NY

	WI	SP	SU	FA	AN
Insol.	65	175	216	113	141
Wind (D)	95	119	72	68	89
Wind (N)	152	98	33	82	92
Wind (T)	247	217	105	150	181

North Omaha, NB

Insol.	85	201	263	131	170
Wind (D)	63	119	53	67	76
Wind (N)	86	60	23	46	54
Wind (T)	149	179	76	113	130

Phoenix, AZ

Insol.	141	294	325	197	239
Wind (D)	13	30	23	18	21
Wind (N)	13	14	17	11	14
Wind (T)	26	44	40	29	35

Santa Maria, CA

Insol.	118	244	294	175	208
Wind (D)	23	70	43	28	41
Wind (N)	16	13	4	9	11
Wind (T)	39	83	47	37	52

Seattle-Tacoma, WA

Insol.	40	167	233	90	133
Wind (D)	38	53	33	31	39
Wind (N)	72	37	17	44	43
Wind (T)	110	90	50	75	82

Washington, DC - Sterling, VA

Insol.	79	185	231	127	156
Wind (D)	49	62	28	31	43
Wind (N)	55	35	10	24	31
Wind (T)	104	97	38	55	74

Section IV

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