Appendix B

METHODOLOGY

Data Collection

GeoResearch, Inc., developed the *Montana Wind Energy Atlas* by assembling, at the outset, a comprehensive wind data base. This data base is the most complete of its kind existing for Montana. Major data sets obtained include those from the following sources:

- The Montana Air Quality Bureau (AQB) maintains a large data file, which includes wind speed and wind direction data, as well as data for many other meteorological and air quality parameters. Most of the data were gathered by the AQB as part of studies conducted to measure air quality in Montana. Some of the data were collected by private companies and submitted to the AQB to comply with air quality permit regulations.
- The Bureau of Reclamation (BOR), U.S. Department of the Interior, operated five wind monitoring sites in Montana as part of its Northern Great Plains Wind Energy Study. These data were obtained for use in preparing the *Montana Wind Energy Atlas.* BOR later reduced data from the sites run by the Montana Department of Natural Resources and Conservation (DNRC).
- The National Climatic Center (NCC) in Asheville, North Carolina, provided wind data gathered by the National Weather Service (NWS), the Federal Aviation Administration (FAA), and the United States Air Force (USAF). These agencies have collected wind speed and wind direction data at airports for many years. The data are collected primarily for aviation and weather forecasting purposes. Wind speed and wind direction data are collected each hour and disseminated over a nationwide data gathering system. These data are intended to represent a mean value of wind speed and wind direction during the minute preceding the observation.
- The Battelle Pacific Northwest Laboratory, under a contract with the U.S. Department of Energy, obtained the NWS, FAA, and USAF data from the National Climatic Center and analyzed these data. Selected Battelle analyses were used in preparing the *Montana Wind Energy Atlas.* Battelle Pacific Northwest Laboratory also provided one year of wind monitoring data from the Livingston Candidate Wind Turbine site. The Livingston data include hourly wind speed and wind direction averages at 10.0, 30.0, and 45.7 meters above ground level. These data have been analyzed and included as part of the *Montana Wind Energy Atlas.*
- The Montana Power Company provided 18 months of data from their Salem site. The Salem data include hourly wind speed and wind direction averages at 10.0, 30.0, and 100.0 meters above ground level. These data also have been analyzed and included as part of the *Montana Wind Energy Atlas.*
- The Bonneville Power Administration (BPA) provided hourly data on three sites in their Wind Regional Energy Assessment Program (REAP). These data are in the data base at the Wind Resources Assessment Laboratory, Oregon State University.

In addition to these data, available in machine-readable form, a considerable amount of useful data was obtained in hard copy from other sources.

Data from these previous monitoring efforts were examined and evaluated. When the data files were examined, data from some sites were found to contain a significant number of errors. If a site was located in an area of low potential and other monitoring sites were nearby, data from that site were not analyzed. If no sites were nearby, the data set was screened and efforts were made to delete invalid data. If after this a significant amount of the data remained suspect, the data from the site were not analyzed.

Preliminary analyses were conducted, when feasible, for all sites with a solid data set. Detailed analyses then were performed for all sites that indicated a high wind potential. These various analyses are discussed below.

Data Analyses

Several types of wind analyses were performed for all sites except those previously analyzed by Battelle. For those sites, the Battelle analysis simply was reproduced. The extent of the analysis for a particular site depended on whether the site was considered "high potential." For purposes of this *Atlas,* a site was defined as "high potential" if the average annual wind speed at that site was equal to or greater than 11 miles per hour.

An initial screening analysis was performed by computer on all sites for which at least one year of wind speed data was available. The result of this screening was a table showing a percentage frequency distribution of wind speed by month and a similar annual distribution. The analysis also provided information on average monthly and average annual wind speed and power.

To perform the analysis, each hourly wind speed value was evaluated and a running total of the variable representing the appropriate wind speed class was maintained. After all wind speed values had been read, the percentage frequencies of each wind speed class for all 13 periods (monthly plus annual) were computed by dividing the count for the class by the total number of readings for the period and multiplying the result by 100.

This computer program also calculated average monthly and average annual wind speeds by summing the individual wind speeds and dividing this sum by the total number of readings. To obtain the average monthly and average annual wind power values, the sum of the wind speed cubed was obtained from the data file. Once these monthly sums were obtained, the average wind speed cubed was calculated by dividing this sum by the number of observations. The average wind power was then calculated from:

$$P = 1/2 \rho V^3$$

where:

$\bar{P}$ = average wind power (watts/m^2);

ρ = air density (kg/m^3) = 0.3488 (station pressure (mb))/(station temperature (K));

$\overline{V}^3$ = average wind speed cubed.

Since temperature and pressure at the monitoring sites were not available for this analysis, average values were used. For pressure, the value used was computed from:

$$P = P_0 (1\text{-}0.0226z)^{5.25}$$

where:

P = station pressure;

P_0 = standard sea-level pressure;

z = station elevation (km).

For temperature, average statewide values for each month were used. Table B-1 lists the pressure values for each site, while Table B-2 shows the temperature values for each month. (The Battelle analysis, since it was limited to NWS, FAA, and USAF weather stations, was able to use actual temperature and pressure data.)

Finally, anemometer height, the total number of valid observations, and the percentage of data recovery were presented for each site.

For the Livingston Candidate and Salem sites, where the wind speed actually was measured at higher levels, average wind speed and wind power were calculated using the same method used for the 10-meter tables. In addition, for these sites actual power law exponents were calculated for comparison with the one-seventh power law. Methodology and results of these power law analyses are presented in Chapter V.

Once the preliminary screening analysis was complete, the tables were examined to determine those sites to be further analyzed as high potential sites.

The first analysis performed for the high potential sites was the calculation of percentage frequency distributions of wind speed by hour and by season. In these tables, accompanying the discussion of these sites (Chapter IV), hourly periods are listed according to the time (Mountain Standard Time) at which the given period ended (e.g., hour 1 represents the time period 0001 - 0100, etc.). The four seasons are defined as:

- Winter — December, January, and February
- Spring — March, April, and May
- Summer — June, July, and August
- Autumn — September, October, and November

To analyze these distributions, a wind speed class was computed, and a running total was kept of the variable representing that class, hour, and season. In addition, the sum of wind speeds for each hour and season was computed. Once all wind speed values for a site had been read, the percentage frequencies for each wind speed class,

Table B-1
Sites Analyzed for the Montana Wind Energy Atlas
Average Station Pressure (millibars)

County	Site	Pressure
Big Horn	Decker Coal #8	892
	Spring Creek #1	880
	Westmoreland Absaloka #2	890
Broadwater	Three Forks	859
Cascade	Salem	898
Chouteau	Highwood Bench	905
Daniels	Scobey Border	926
	SCOBEY HANRAHAN	915
Dawson	GLENDIVE MICROWAVE	921
Deer Lodge	ANACONDA C-HILL	776
	Anaconda Highway Junction	840
	Anaconda Mill Creek	837
	ANACONDA WEATHER HILL	800
Flathead	Big Prairie	888
	Columbia Falls Water Supply	904
Glacier	CUT BANK	888
Jefferson	Microwave Tower	863
Lake	Ronan Nine Pipes	907
Missoula	Missoula Hoerner-Waldorf #1	903
	Missoula University of Montana	901
Park	LIVINGSTON CANDIDATE WIND TURBINE SITE	834
Powder River	Broadus Randall Ranch	904
Rosebud	COLSTRIP BN	900
	Western Energy #12	891
Silver Bow	Butte Hebgen Park	827
Teton	Choteau	852
Valley	Fort Peck	931
Wheatland	JUDITH GAP	852
Yellowstone	Laurel New Farm	901
	Shawnee Park	904

NOTE: Capitalized site names indicate high potential sites.

Table B-2
Sites Analyzed for the Montana Wind Energy Atlas
Monthly and Annual Average Temperature (degrees Kelvin)

January	264	July	293
February	268	August	292
March	272	September	287
April	276	October	281
May	283	November	276
June	287	December	268

Year 280

hour, and season were computed, and the average wind speed for each hour and season was calculated. A frequency distribution and an average speed for all hours also were calculated.

A second analysis performed for high potential sites was the calculation of an annual joint frequency distribution of wind speed and wind direction (the wind rose distribution). To perform the analysis, matching wind speed and direction values were read from the data file. A wind speed class and a wind direction class were calculated, and running totals of variables representing different wind speed and direction categories were kept. After all data had been read, percentage frequencies of each category were computed by dividing the count for each class by the total count.

A measured wind speed distribution, such as those provided in this *Atlas*, may be approximated by an analytical distribution such as the Rayleigh distribution:

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

where:

$p(V)$ = probability density of wind speed (fraction per m/sec);
V = wind speed;
$\bar{V}$ = long term average wind speed.

The Rayleigh distribution is a special case of the Weibull distribution. This more complicated distribution, in many cases, provides a better approximation of the measured wind speed distribution. The Weibull distribution is given by:

$$p(V) = \left(\frac{k}{c}\right)\left(\frac{V}{c}\right)^{k-1} \exp\left\{-\left(\frac{V}{c}\right)^{k}\right\}$$

where:

$p(V)$ = probability density of wind speed (fraction per m/sec)
c = scale factor related to the mean wind speed ($\bar{V}$) by
$\bar{V}$ = $c\,\Gamma(1+1/k)$, where:
Γ = the gamma function, $\Gamma(n) = (n-1)!$, and
k = shape factor related to the variance of wind speed (σ_V^2) by
$\sigma_V^2 = c^2\{\Gamma(1+2/k) - [\Gamma(1+1/k)]^2\}$

For the high potential sites in this *Atlas*, the Weibull parameters c and k have been calculated from the monthly wind speed distributions by means of a least-squares fit to the observed distribution. This method requires that wind speed categories be of equal size. The data files from which the percentage frequency for wind speed categories was obtained, however, contain wind speed categories of unequal size: one mile per hour increments between 0 and 20 miles per hour; five mile per hour increments between 20 and 40 miles per hour; and a final category of wind speeds exceeding 40 miles per hour. For wind speeds between 20 and 40 miles per hour, therefore, the wind speed frequency for each five mile per hour increment was divided by five, assuming an equal distribution over that increment. For wind speeds greater than 40 miles per hour, the category was assumed to be centered on 42.5 miles per hour.

The method of differential corrections was used to fit values of c and k to the observed wind speed frequency distribution derived from the data file. This is an iterative method in which the values of the Weibull probability density function and its derivatives with respect to c and k are computed from an initial guess of c and k. From these values, corrections are computed and added to c and k. The process is repeated several times until accurate values of c and k are obtained.

These Weibull coefficients are useful primarily for meteorological modeling purposes.

Site Selection

Analyzed sites were selected for inclusion in Chapter IV of the *Atlas* according to the following criteria:

- All high potential sites (e.g., those with average annual wind speeds greater than or equal to 11 miles per hour) were included;
- In general, sites with less wind potential also were included when one year's data or more were available, except that in areas with many sites, such as Missoula and Anaconda, one or two representative sites were selected to characterize the wind potential in the area;
- Sites with low data completeness generally were not included. If a more complete data set for the area was not available, however, a site with low data completeness was included, with caveats, based on the assumption that some data for the area are better than none.

Sites not included in Chapter IV of the *Atlas*, either for lack of a solid data set for analysis or for the reasons outlined above, are discussed briefly in Appendix C.