HDR

April 7, 1997

Mr. Richard Halet
Northern States Power Company
414 Nicollet Mall, 8th Floor
Minneapolis, MN 55401

RE: NSP Phase II - 100 MW LWECS
Microsițing Analysis Report
08512-001-164 WAKE

Dear Mr. Halet:

Enclosed for your distribution and use are 9 copies of the Micrositing Analysis report. The methodology discussed therein resulted in the final tower locations as shown on the included site plan (Dwg. No. SP-2 Revision B).

With submittal of this report, ZOND Minnesota Development Corp. II fulfills the requirements of Paragraph III.F.1. of the EQB Site Permit No. NSP-WGR-1-95.

Questions concerning the report should be addressed to my attention at the HDR address shown below.

Very truly yours,

James W. Booty

James W. Booty
Project Manager

JWB/jmg

Enclosures

c: Tom Biernat (encl.)/Loretta Haynes (encl.)
Rich Simon

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NSP PHASE II - 100 MW LWECS

LAKE BENTON, MINNESOTA 56149

MICROSITING ANALYSIS

PERMIT NO. NSP-WGR-1-95

ZOND Minnesota Development Corp. II

13000 Jameson Road
Tehachapi, CA 93561

April 7, 1997

■ RICHARD L. SIMON, M.S.
Consulting Meteorologist

14 March 1997

Mr. Thomas Biernat
Zond Development Corporation
P.O. Box 1910
Tehachapi, CA 93581

Re: NSP Phase II

Dear Tom:

In accordance with the MEQB Site Permit for the NSP Phase II wind turbine project, I hereby submit the micrositing and wake analysis used to optimize the 143-unit turbine array. There is no guidance as to the level of detail required for this report, so I have summarized the processes in general and provided fairly thorough comments on micrositing and wake analyses, which are two components of the complete process.

The ultimate basis for the wind resource assessment is NSP's 30-meter anemometer tower known as Holland, located 10-15 miles southeast of the project site. Winds have been measured at this tower since 1985. Through September 1996, the composite long-term mean annual wind speed at the
30-m level of this tower was 15.87 mph.

Zond began measuring winds in the NSP Phase II area northwest of Lake Benton in May 1994. There were initially nine towers, ranging in height from 33-90 feet. That summer seven 130-ft towers were installed, with winds measured at three levels (33, 90, 130'). In 1995 another nineteen towers were added--all 130 feet except two at 240 feet.

Of the 35 Zond meteorological towers, 25 are within the Phase II array or adjacent to it. The attached map shows the location of these anemometer stations.

Zond's station located in the northeast quarter of Section 36 (Drammen Township) was designated as the key on-site reference anemometer for Zond's wind resource assessment. It is designated as Site LB-2, and it has a single 36-ft measurement level. This site was chosen because of its topographical similarity to NSP's Holland anemometer: atop the primary ridgeline of Buffalo Ridge.

Indeed, winds at Zond anemometer LB-2 and Holland have proven to be well correlated. The linear correlation coefficient of daily mean wind speeds between the two sites has consistently exceeded 0.90.

Because of this excellent correlation, the estimated long-term mean annual wind speed at LB-2 is computed directly from its overall mean speed ratio to Holland. The resulting value based on nearly 2½ years of data is 13.79 mph.

Winds measured at all Zond anemometer stations were compared against LB-2. In particular, overall mean wind speed ratios were computed for all stations and all levels. This ratio was used to estimate long-term mean annual wind speeds across the wind monitoring network.

In this manner, long-term mean wind speeds were estimated up to 130 ft above ground (two stations to 240 ft) at all Zond anemometer stations. Since the initially planned hub height of the Phase II project is 50 meters (164 ft), it was necessary to adjust all wind speed estimates to that height. This is done by means of the wind shear exponent, a number deriving from a power law equation:

$V1/V2 = (Z1/Z2)$ where V1 and V2 are mean wind speeds at levels Z1 and Z2 above the ground, and "b" is the power law exponent

Over flat terrain, conventional theory predicts the wind shear exponent will be 0.14. The range of <u>observed</u> wind shear exponent at Zond's 25 meteorological towers extending to at least 130 ft was 0.14-0.23, with the bulk of sites in the middle of the range. Thus the shear at Buffalo Ridge is stronger than theory predicts.

NSP also operates several meteorological towers in the vicinity of Phase II; they show the same type of shears.

Even more surprising, it was discovered that the wind shear exponent from the 90-130 ft layer exceeded that from the 33-130 ft layer at *all 25* towers! This phenomenon was used to estimate shears from 130 ft to hub height, but with shears reduced slightly from the 90-130 ft levels for some conservatism.

The attached map shows the results of this process. Estimated long-term mean annual 50-m wind speeds are shown with thick marker pen at all Zond anemometer stations.

A review of these data, plus NSP wind studies prepared by their meteorologist Ron Nierenberg, reveal several consistent trends in wind resource along Buffalo Ridge:

1) the primary ridgeline of Buffalo Ridge generally has ambient (wake-free) winds equal to or better than the Holland reference anemometer, except where the ridge becomes extremely flattened

2) sloping areas on either side of the primary ridgeline generally have less winds than Holland. This effect is ameliorated on so-called "secondary" ridges on the northeast side of the primary ridgeline, especially where they are perpendicular to the prevailing south-southwest winds.

3) the west side of the primary ridgeline tends to have a lower wind resource than the east side for the same elevation and topographic setting

With the above in mind, plus numerous site visits to examine topographic features first-hand and document other factors which influence the wind flow (e.g., trees), the wind turbine array was laid out.

Also considered in this process were residences (minimum 1000-ft setback to minimize noise impact) and public roads (minimum 250-ft setback).

Another important input was the frequency and strength of winds from various directions was carefully examined to select the best orientation for turbine rows in order to minimize wake losses. It was determined that row orientations from west/east through northwest/southeast would be the most favorable.

It is hard to detail all the procedures and thinking that goes into planning a 100-MW wind farm array. It is an iterative process, with constant input from engineering and other disciplines. Further, the winning array submitted as part of the Phase II bid was prepared in December 1994 and planned without benefit of all the subsequent meteorological data. Thus various amendments were made to account for the new meteorological data and even improved turbine characteristics.

Plus the MEQB permit stipulated that the final array be contained within a designated footprint. Once this requirement was accepted, then the goal was to optimize the array within the allotted area.*

But the basics of the array are clear upon examination of the map. Turbines are laid out in rows atop ridgelines roughly perpendicular to the prevailing winds. Higher ground is used whenever possible, and nearly all turbines lie atop Buffalo Ridge itself or on its northeast side (on secondary ridges).

Within each row, turbines are a minimum 600 feet apart (3.8 rotor diameters), with fourteen exceptions as allowed by the MEQB permit. This separation will help reduce wakes when winds do blow parallel to the turbine rows.

And the turbine rows are widely separated, often only one row in each section of land. Where there are two or more rows in a section, they are separated by a minimum 11 rotor diameters.

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* subsequent wind data collected by Zond suggests that other nearby areas might be windier, but it was not possible to utilize such areas.

Long-term ambient mean annual 50-m wind speeds are shown for each turbine site on the attached map. They have been derived based on the anemometer data, terrain variations, and surface roughness considerations (e.g, trees, buildings). Considerable time was spent in the field to prepare these estimates--the topographic map does not always accurately portray actual field conditions.

The array selected and refined by Zond not only meets the necessary wind resource objectives, but it also accounts for construction and other costs.

The next step in the wind resource assessment was to estimate long-term energy potential of the project. This was done by scaling the multi-year wind speed frequency distribution at Holland to projected hub-height wind speeds across the project, then applying the Zond Z-48 performance curve at the appropriate annual mean air density (1.196 kg/m^3). Combining the results for individual turbines yielded an aggregate long-term gross annual projection.

Net projections take into account various discount factors which reduce actual energy from that determined solely by mathematically combining wind speed and turbine performance curve data. These discount factors include turbine availability, transformer/line losses, turbulence, blade contamination, icing and wake losses.

There are two types of wake losses to consider in a project like this. The first is the so-called row-to-row wakes; i.e., when winds blow from one turbine row to another. In such cases, the downwind row receives less than ambient wind. The second type of wake loss is often referred to as "in-line" or "off-axis" wakes, since the winds are blowing off their normal prevailing axis.

Researchers have used various empirical field studies and mathematical models to estimate wake losses. The techniques used in this study are as follows:

For row-to-row wake losses, a truncated version of the GTAP (Generalized Terrain Array Performance) model was used. This combined flow and wake model was developed under a five-year grant by the U.S. Department of Energy from 1986-1990. The study was headed by United Industries Corporation, and I served as an active subcontractor. The wake component of this model was successfully verified at seven California wind farms, where actual wake loss data were available from field studies funded by DOE and the local utilities.

To explain the model's rather complex mathematics is obviously a challenge, especially for an audience not well-versed in such matters. However, the following three general rules apply reasonably well to row-to-row wakes:

1) the percentage wind speed deficit at downwind rows is fairly constant for a given wind turbine model, regardless of the strength of the wind

2) wake losses are inversely proportional to lateral spacing within the upwind row (e.g., a row with 2 rotor-diameter spacing will cause twice the wake loss on downwind turbines as a row with 4 rotor-diameter spacing)

3) wake losses decay exponentially downwind. Typically in the mathematical formulation one sets a threshold (on order of 0.2%) at which this term is disregarded. At 3.8 rotor diameter spacing, this threshold is met at approximately 40 rotor diameters downwind.

As an example, consider the two rows of turbines in the south half of Section 8. The southwest row of four turbines has 192-m spacing (4.0 rotor diameters), and the distance to the downwind row (assuming southwest winds) is 552 m (11.5 rotor diameters). When such winds blow, the speed deficit at affected turbines in the second row is calculated by the model at 2.8%. This is the largest row-to-row wake loss estimated for the array. And it will occur only when winds are blowing directly from one row to the next.

The estimated aggregate wake-induced speed deficit for the entire array is 0.8%, taking into account the frequencies of critical wind directions. This is equal to a 1.3% decrease in annual energy.

The mathematical treatment of off-axis wakes has not been established to my satisfaction. I rely on field studies performed by DOE in the 1980's, which showed that energy production was reduced by 50% when winds blow exactly parallel to turbine rows with 2.0-rotor diameter spacing.

My model incorporates that basic fact. To estimate off-axis wakes, one first prepares a so-called "wind power rose." This we prepared from all Zond data over the 2½-year record. This wind power rose computes theoretical energy for each of 16 compass point sectors (North, North-northeast, Northeast, etc.). Then for given row orientations, it computes the percentage energy when wakes from one turbine can impact the next turbine in the row. In the case of 3.8 rotor diameter spacing, this includes all directions ±20° from the axis of orientation. The 50% loss is adjusted inversely by the lateral spacing (e.g., loss at 3.8 RD = 50% x 2/3.8, or roughly 26%), and to account for the percentage of the rotor disk engulfed by the subject wake for a given off-axis angle.

Here are the resulting off-axis wake losses for a turbine sandwiched in between two other turbines, at 3.8 rotor diameter spacing:

Row Orientation	Percent Wake Loss
W/E	2.28
WNW/ESE	3.31
NW/SE	3.73
NNW/SSE	4.14

Note these percentages differ from those originally calculated based on the Holland data through mid-1994, which is what was available at the time of the bid.

Off-axis wakes were calculated for every turbine row. Note that in a given row, there is always one turbine not experiencing such wakes. And certain isolated turbines are effectively not exposed to such wake losses.

The array average off-axis wake loss is estimated at 2.2%.

Total wake losses for the entire project will be the sum of the row-to-row wakes (1.3%) and off-axis wakes (2.2%), or 3.5%. This is an extremely low wake loss compared to most projects. And the uncertainty with respect to wakes (±1.5%) is minor compared to the uncertainty in being able to specify the average ambient energy potential across the array, which is almost a full order of magnitude greater.

Sincerely,

Richard L Simon

Richard L. Simon

SITE MAP