MACRO-SCALE WAKE EFFECTS

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ABSTRACT

This report will focus on the results of two separate studies conducted in the Altamont Pass. One was a federally funded U.S. Department of Energy (DOE) study[1] on wake effects and the other was a privately funded study on macro-scale wake effects.

In the DOE study, rows of turbines were switched on and off to measure wake energy deficits at downwind rows. The average energy deficit between rows was about 12%. Energy deficits were inversely proportional to wind speed.

The investigation of macro-scale wake effects examined the energy deficits from several large arrays of wind turbines. The wake deficits from these turbine arrays persist for five km (3 miles) or more, i.e., several hundred rotor diameters, thus the term "macro-scale". The wake deficits extend much further downwind than was previously predicted by models.

PART 1 - DOE WAKE DEFICIT MEASUREMENTS

Results of the DOE study that are pertinent to the subject of macro-scale wakes are presented here. There were three test arrays used in the DOE wake study. Each test array consisted of three or four rows of Nordtank 65-kW turbines, with five turbines per row. Lateral spacing between turbines within rows was 1.9 rotor diameters (RD). Spacing between rows varied from 6.8 RD to 10.2 RD with an average of about 8.5 RD. Approximately 125 hours of wake energy deficit data were collected and analyzed. The data collected were 10-minute averages of energy production at each turbine.

Wake Deficit Measurement Results

In the basic test scenario, with mean wind speeds of 10 mps (22.4 mph), the mean row energy deficit was 12.3%, at approximately 8.5 RD. Higher deficits were measured in lower wind speeds, i.e., higher thrust coefficient (C_t). Figure 1 is a plot of the mean row deficits vs. free-stream wind speed for each test. The regression line shows the inverse relationship between wind speed and energy deficits. The correlation coefficient between wind speed and mean row deficits was -.92. Thus wind speed variation alone explained 85% of the variance in the deficits. The magnitude of the correlation between the deficits and the coefficient of power (C_p) was about the same; .94. Therefore the deficits were a function of a combination of wind speed and turbine performance characteristics such as C_p and C_t. The remaining 15% of the variance in the deficits was probably due to factors such as turbulence, terrain and stability effects.

There was considerable variation in individual turbine energy deficits within each test row. Terrain enhanced and diminished ambient flow conditions. Turbines at sites with poor exposure had lower energy production and higher energy deficits. Terrain effects can significantly compound or increase wake deficits. This is an important finding for siting wind turbines because a terrain related low wind site is likely to experience higher deficits than a high wind site.

Sixteen Rotor Diameter Test Results

Several tests were conducted to measure the effects of a single row of turbines with an upwind spacing of 16 rotor diameters, double the normal spacing in these arrays. In 10 mps (22.4 mph) winds, the energy deficits were 12.1%, almost exactly the same as in the 8.5 RD tests. This is rather remarkable as computer models have predicted lower deficits at greater distances. Many computer models predict that deficits should be inversely proportional to the distance (downwind) squared. Thus, if the distance doubles, the deficits should be reduced to 1/4. This was clearly not borne out by the measurements.

The inverse square assumption inherent in many computer models treats wakes as point sources which can expand (i.e., diffuse) infinitely in the vertical and horizontal planes. However, rows of turbines are line sources, not point sources, and if there is little variability in the wind direction, wake expansion in the horizontal plane will be quite limited.

The climatology of the Altamont Pass may also help to explain these results. It is characterized by the presence of a strong temperature inversion during the high wind season. An inversion occurs when there is a layer of warm air above a layer of cooler air. The base of this temperature inversion is normally found in the first 100 meters (330 ft.) above ground level. Within the inversion, there is a negative wind shear, i.e., wind speed decreases with height. There is little wind energy above the top of this inversion layer, approximately 200 meters (660 ft.)above ground level. The air in the inversion layer is very stable, so there is little vertical mixing. Thus, there is little replenishment of momentum from above a turbine wake and limited expansion of the wake in the vertical plane.

Wake expansion is restricted in the horizontal plane because the wakes are generated by rows of turbines. In the Altamont Pass the expansion is also restricted in the vertical due to the shallow stable layer. The inverse square assumption used in many computer models is inappropriate under these circumstances. If the wake can not expand in either the horizontal or vertical plane, it does not diffuse or erode, and this explains its persistance.

The results of these tests help explain the very persistent macro-scale wakes discussed in Part 2, below. The deficits from these 16 RD tests are also plotted on Figure 1. The figure shows that these data points lie near the regression line of the 8 RD tests. Regression analysis of the 16 RD deficits suggests that these deficits are more sensitive to changes in speed than the 8 RD deficits. The analysis also suggests that the energy deficits would be negligible in wind speeds above 14 mps (31 mph).

PART 2 - MACRO-SCALE WAKE EFFECTS

About five years ago a perplexing phenomenon was observed: each year the winds in certain parts of the Altamont Pass decreased. Initially the cause was thought to be climatological. For instance, in 1984 the low winds were blamed on the "El Nino" (abnormally warm waters in the equatorial east Pacific Ocean). As more time has passed, the winds at many locations still have not returned to earlier levels, while other areas have remained at historical levels. Although variations in climatological conditions can cause improved or reduced winds from year to year, another explanation for the diminished wind resource has emerged. The large arrays of wind turbines installed in the Altamont Pass produce significant wake energy deficits that persist much further than 10 or even 20 rotor diameters (RD) downwind. In the previous section empirical data showed that wake deficits at 16 RD downwind were essentially the same as those at 8 RD. This section presents evidence that supports the hypothesis that wakes persist for even greater distances. The supporting data were collected and analyzed on behalf of Howden Wind Parks Inc.

The impact downwind of a 50 MW windpark, which was installed upwind of the Howden Wind Park (HWP) in late 1985, has been examined. Crosswind or lateral spacing in the 50 MW array is approximately 1.3 RD, which is unusually tight by Altamont standards. The mean wind trajectory passes through the 50 MW array to the HWP about 90% of the time (on an annual energy basis). Figure 2 is a topographic map which shows the location of the 50 MW array in the northern Altamont Pass. The figure shows the approximate locations of the turbine rows in the array (wavy lines).

The data used in the analysis were hourly mean wind speeds for summers (May-Sept.) of 1985 and ´86. A comparison was made between summer 1985, before the two wind parks were installed, and 1986, after they came on-line. The data period excluded times when the HWP was operational, so no wakes from these turbines were present. Theoretical energy for these two periods was calculated using data from numerous anemometers and the Howden 330-kW power curve. The use of different power curves had negligible effects on the results. The changes in theoretical energy, in percent, from summer 1985 to 1986 have been plotted at the various anemometer locations and contoured on Figure 2. The locations of the contours are based on the available data and are estimated where there is none. Note the arrow extending downwind of the array which shows distance in rotor diameters (upwind turbine diameter).

Figure 2 shows a number of interesting things:

1) Immediately downwind of the 50 MW array, the energy decrease or deficit is 20%.

2) A large area, extending 5 km (3 miles) or 250+ RD

downwind of the 50 MW array has a deficit of about 15%. The deficit may continue even further downwind, but this can not be determined as there are no additional sensors any further back.

3) The areas to the northwest and southeast of the 50 MW array (crosswind) have negligible (0 to 1%) energy decreases.

These deficits are for the summer season only when the wind direction is predominantly southwest. Annual deficits are slightly lower, due to varying wind trajectories.

One may ask about repeatability of these results in subsequent years. A single anemometer has operated continuously since 1984 in the middle of the HWP. (The 1988-89 data have not been examined because the HWP was operational and the local wakes would effect this anemometer.) Theoretical energy for the summers of 1984 and 1985 (before installation of the 50 MW windpark) have been compared with theoretical energy in 1986 and 1987 (after). This anemometer site had a 9% energy drop in 1986-87 compared to the first two-year period. However, sites that are crosswind to and upwind of the 50 MW array showed an energy <u>increase</u> of 9% to 10% for the 1986-87 period. Thus, the site within the wake-effected region has dropped almost 20% in theoretical energy, relative to the freestream sites.

The climatology of the inversion was discussed in the 16 rotor diameter section above. The high wind layer is near the ground and only extends up a few hundred meters. Due to the shallow layer the amount of wind energy flux in the Altamont is finite, and each row of turbines removes a portion of this energy, <u>permanently</u>. Based on extensive vertical wind shear measurements, the total power in the column of wind passing over the 50 MW array can be calculated. This is done by integrating the cube of the wind speed over a vertical plane, normal to the flow. The calculation yields approximately 200 MW of wind power flux in the column, on a typical day during the high-wind season. The 50 MW array may extract 25 MW or more from the column, or about 12.5% of the total available power. Additional losses are caused by waste heat, friction, drive train inefficiency and conversion of kinetic energy to turbulent energy.

<u>Macro-Scale Wakes - Additional Examples</u>

There are other examples of this phenomenon in the Altamont Pass. The HWP became operational again in spring of 1988. Using similar analysis techniques, theoretical energy deficits of 20% to 30% were measured in summer 1988, compared to summers 1986-87, 1.6 km (one mile) or 50 Howden RD downwind of this installation. Figure 3 is a topographic map showing the location of the HWP and its´ wake deficit. The figure shows the approximate locations of the turbine rows. Note the arrow extending downwind of the array which shows distance in Howden rotor diameters. The figure shows that immediately downwind of the array, there is a 37% energy deficit. At a distance of 1.6 km (1 mile), or 50 RD there is a 22% deficit, and at 2 km or 60 RD the deficit is 19%.

A similar situation occurred in the central Altamont Pass at the Castello Ranch. An array (four rows) was installed upwind of this ranch in 1986. Using similar analysis techniques, theoretical energy deficits of 30 to 40% were measured. The deficit immediately downwind of the array, at 8 RD was 40%. At a distance of 1.2 km or 40 RD, the energy deficit was 29%.

Mr. Robert Baker, with Pacific Wind Energy, formerly with U.S. Windpower Inc., reported similar findings in the San Gorgonio Pass, near Palm Springs, in southern California. He presented these data at the AWEA/Retsie Conference on June 7, 1988. Mr. Baker reported that he had measured a 7% velocity deficit, 30 RD downwind of an array of Nordtank turbines. A 7% velocity deficit is equivalent to a 22.5% power deficit and approximately a 15% theoretical energy deficit. These findings are of special interest because the San Gorgonio Pass is not subjected to the very low inversion found in the Altamont Pass. An inversion may be present at night, but probably at higher levels than found in the Altamont. The layer of wind moving through the San Gorgonio Pass is believed to be deeper than the layer in the Altamont Pass.

CONCLUSIONS

There are several important implications of these findings to wind energy developers. First, it helps to explain the decrese in wind speeds in many parts of the Altamont since turbines were first installed in 1981. Second, due to the inverse relationship between wind speed and wake deficits discussed in Part 1, turbine array effects can amplify downward trends in wind speed caused by climatological variations. That is, in a low wind year, wake effects will be worse, and downwind sites will experience larger energy deficits. Third, long-term estimates of the wind resource must be adjusted to account for upstream wake deficits. A historical wind data record at one site, spanning many years but subjected to upstream development for some portion of the total duration, can not be treated as one continuum. The data need to be analyzed in discrete time segments, corresponding to periods with and without upstream development. Otherwise the upstream wake effects will not be accounted for and estimates of the wind resource will be too optimistic. And finally, developers should keep in mind the potentially detrimental effects of future projects installed upstream of their existing or planned projects. The extent of any macro-scale wake effects will depend on the atmospheric stability, overall wind resource, percent of time the wind trajectory is from the upstream development and the size of, distance to and the spacing in the upstream development. The energy deficits in the Altamont Pass may be higher than would occur in other parts of the world. Nevertheless, macro-scale energy deficits could be significant.

ACKNOWLEDGEMENTS

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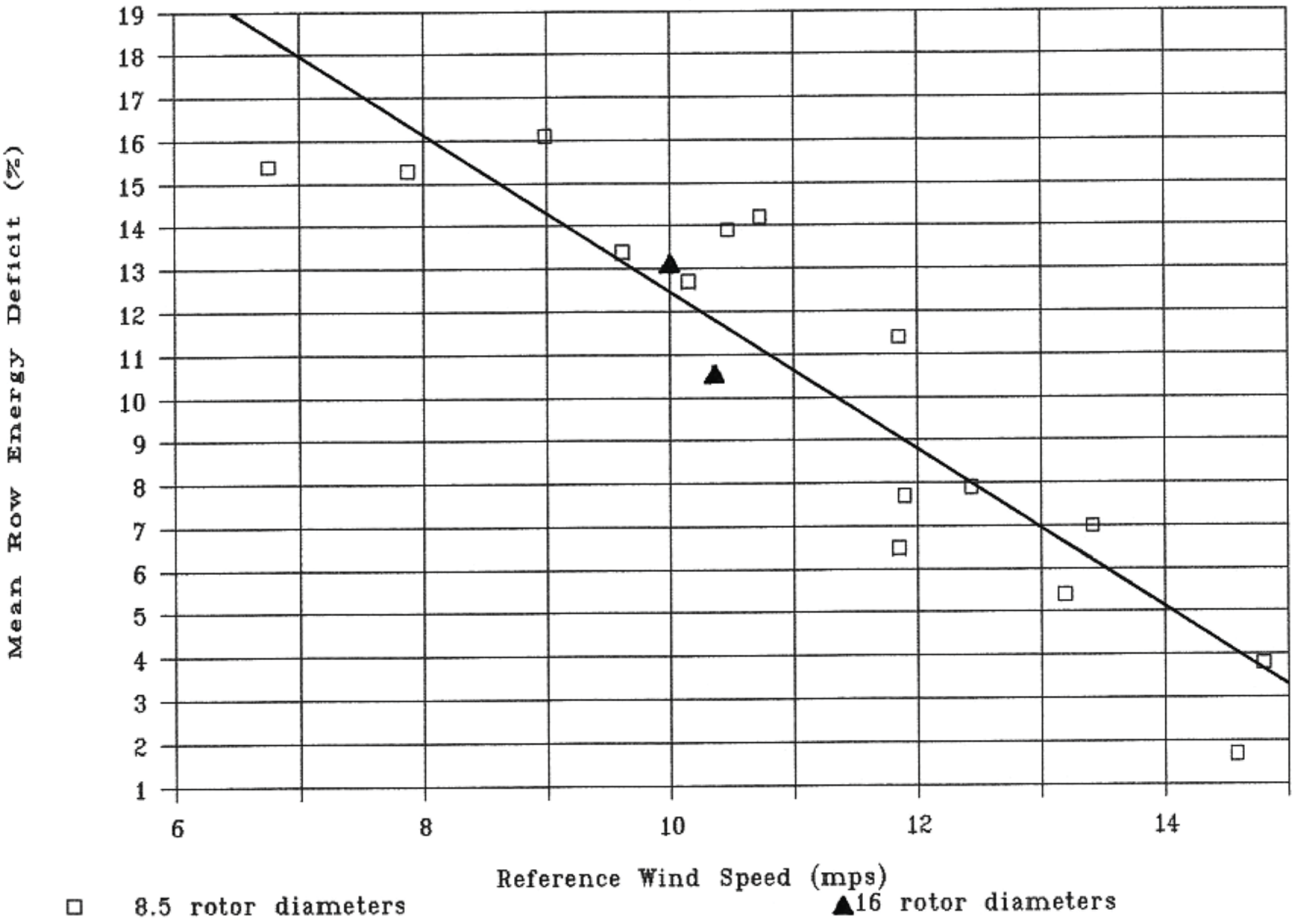
REFERENCES

1. Nierenberg, R., "Wake Deficit Measurements on the Jess and Souza Ranches, Altamont Pass". (1989) Solar Energy Research Institute, Golden, Colorado.

Figure 1 Wake Energy Deficits (%)

vs. Wind Speed (mps)



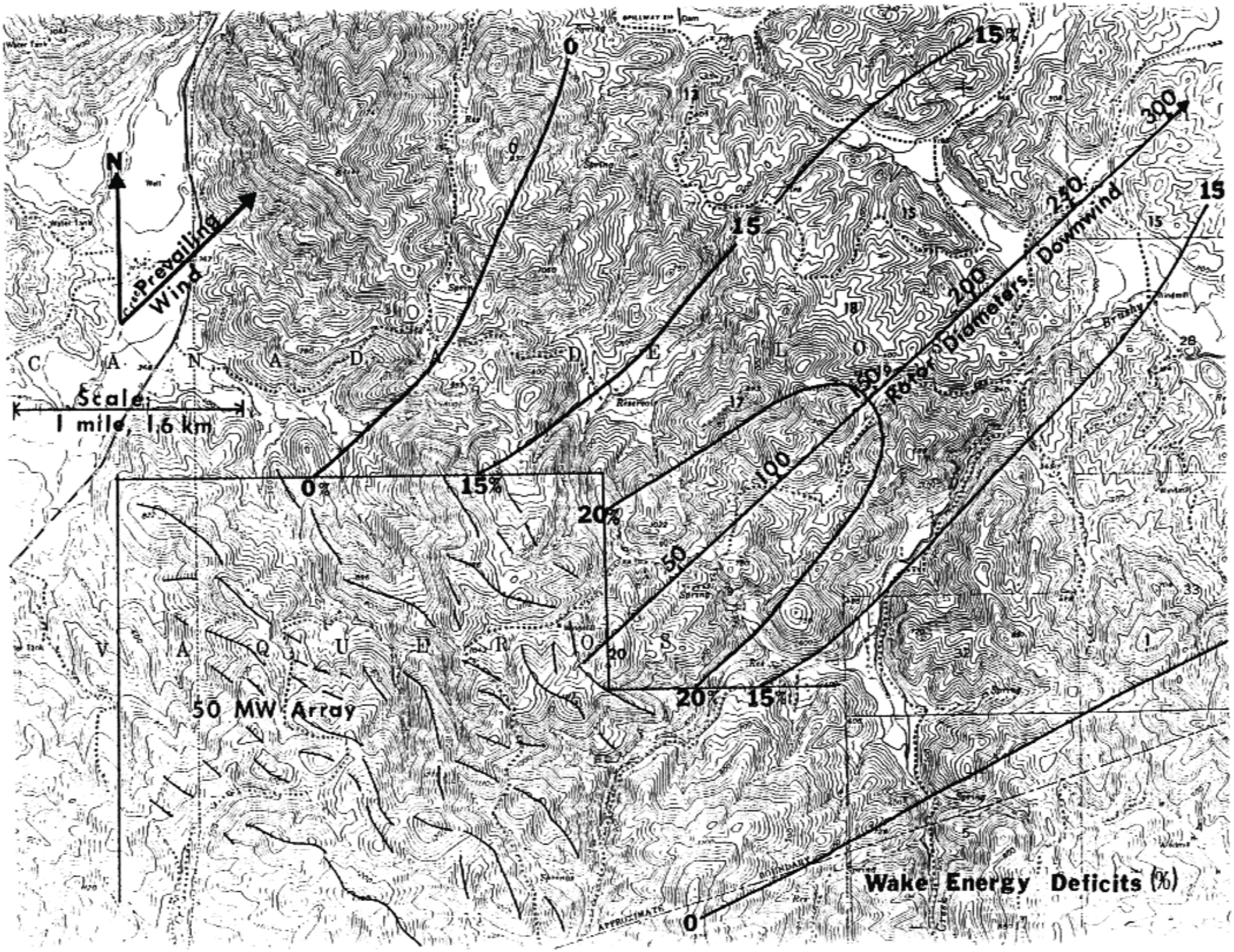


Figure 2. Wake Energy Deficits (%) Downwind of a 50 MW Array

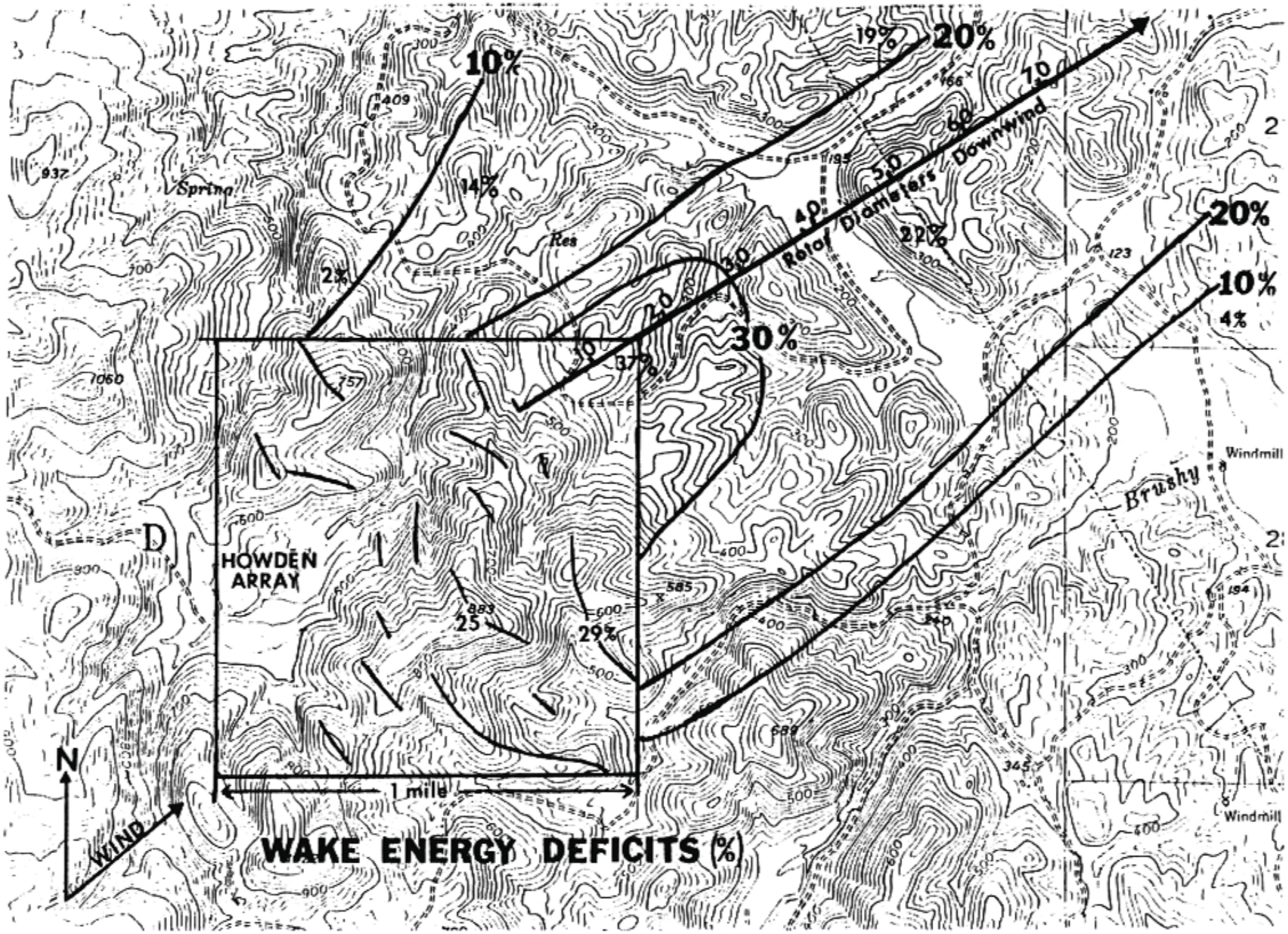


Figure 3. Wake Energy Deficits (%) Downwind of a 25 MW Array