TURBULENCE INCREASES DUE TO WIND TURBINES ON AN OPERATING WIND PARK

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ABSTRACT

During the summer of 1988 a series of wake tests were conducted on the Howden Wind Park in the Altamont Pass of California, located some 80 km east of San Francisco. The tests were designed to determine to what extent the presence of wind turbines affected turbulence levels downstream within the wind park.

An array of eight sets of anemometry were installed to measure wind conditions while turbines upwind were turned off and on. Parameters measured were wind speed, direction, vertical velocity, vertical wind shear (up to 40 m), static stability, and turbine power.

Analysis of two- and four-mintute means and standard deviations shows a high degree of dependence upon stability in several key parameters. Wake-induced turbulence levels as well as wind speed and turbine power deficits are all amplified under stable conditions compared to their levels with unstable lapse rates.

INTRODUCTION

The site where the measurements were made consisted of two rows of Howden 330 kW turbines with 33m rotors on 24m towers. Turbines within rows were spaced at two rotor diameters (RD) and the two rows were separated by approximately 11 RD in the prevailing wind direction. The turbines were sited on top of an elongated hill whose orientation follows the prevailing wind flow. This area was chosen for it's lack of significant terrain features.

The wind data analyzed and presented here were from three of the eight stations used in the study: site W1, located one RD upwind of the first (the upwind) row of turbines measured the free stream wind conditions; sites W8 and W10 (at approximately 8.5 and 10 RD downwind from the first row of turbines) measured wind conditions in the turbine wakes. These two "waked" sites were selected for presentation because they are located at distances (in terms of RD) at which most turbines in California are sited.

The wind measurements were made with R. M. Young propeller-vane anemometers (wind speed and direction) and R. M. Young propeller anemometers (vertical velocity).The instruments were placed on towers at turbine hub height (24m). Vertical wind shear (measured at the W8 location at 14m, 24m, and 40m elevations) was measured using Maximum Cups. Temperature measurements for static stability were made at 10m and 40m elevations at the W8 location using thermistors with radiation shields. Turbine power was measured with a kilowatt transducer. Data was logged with Campbell Scientific 21x loggers sampling all sensors at 1 Hz. Output products were two- or four-minute means and standard deviations.

These data were analyzed for the four possible combinations of conditions using wake (wake/non-wake) and stability (stable/unstable) as the key variables. For the purposes of this analysis, stable conditions are defined as having temperature differences greater than -0.3 degrees C between the 40m and 10m levels. Unstable is defined as having a temperature difference less than -0.3 deg C. The division between stable and unstable at -0.3 deg C is because that is the change in temperature which would occur over a 30 meter height interval in a neutral, or adiabatic, atmosphere.

For the turbulence analysis, the reference wind speeds which were used were from the same location where the turbulence measurements were made. In the other cases, the variables were analyzed with respect to the upstream (W1) wind speed.

TURBULENCE ANALYSIS

The turbulence parameters analyzed were standard deviation of wind speed (here, normalized by the mean to yield turbulence intensity) and standard deviation of vertical velocity. Although not a turbulence parameter, a brief discussion of the mean vertical velocity is also included. The turbulence intensity will be discussed first.

Turbulence Intensity

Free stream measurements of turbulence intensity (Ti) at sites W8 and W10 show patterns which one might expect. The values of Ti decrease as the mean speed increases and overall values of Ti are lower with stable conditions than with unstable, given the same mean wind speed. In actuality, the standard deviation of wind speed tends to increase with wind speed but the increases are not equal to the relative change in wind speed. Hence, Ti decreases with wind speed although the absolute turbulence levels increase.

The introduction of turbine wakes upstream, as expected, increased the turbulence levels at both sites. The relative increases in turbulence from their non-wake values are greater at both sites W8 and W10 in the stable case than the increases observed in the unstable case.

When Ti is plotted versus wind speed, regular and rather consistent patterns are observed. The increases in Ti due to turbine wakes are seen across the entire range of wind speeds. The plotted data also show that the Ti has a high degree of correlation between the two sites for a given wake and stability condition. This is not surprising given the short distance separating the two.

Because of the dependence upon wind speed, an unbiased comparison of turbulence levels for the four conditions must be done over a range of wind speeds common to all conditions. Such a comparison is shown in Table 1 below. The analysis is over the indicated wind speed range at each site. Because the analysis is for a specific wind speed range, the increases in Ti shown are equal to the increases in standard deviation of wind speed over the same range.

TABLE 1. COMPARISON OF TURBULENCE INTENSITIES AT SITES W8 AND W10.
WIND SPEED RANGE = 9.0 TO 12.5 M/S.
MEAN WIND SPEED = 10.5 M/S.

	Unstable		Stable	
	W8	W10	W8	W10
No Wake	.11	.10	.10	.09
Wake	.15	.13	.15	.12
		Change		
Wake/No Wake	31%	26%	42%	43%

One can also analyze turbulence increases as a function of stability. Using the same range of wind speeds as in the above table, percent changes in Ti were calculated for the available range of temperature differences, which was from -0.9 to 0.6 deg C. These calculations showed that there is a surprisingly linear increase in wake-induced turbulence with increasing stability. In the most unstable case, the increase in Ti was on the order of 10% at both sites. At the opposite end of the range, in the most stable case, the increases were on the order of 60% at both sites. The two sites showed very good agreement throughout the range of stabilities analyzed.

It is clear from this analysis that stable conditions result in a reduction in the dissipation of wake turbulence. The good news is that with a stable boundary layer, the overall turbulence levels are lower than in the unstable case.

Vertical Velocity

Vertical component of the wind is not routinely measured for wind energy applications. However, as sophistication of turbulence and turbine fatigue analysis increases, it may prove to be a significant parameter. This would be true particularly in areas where, due to terrain influence, average vertical velocities are consistently non-zero. Turbines can yaw for changes in wind direction, few can tilt for changes in vertical component.

It is interesting to note that at site W10 the mean vertical velocity shows a clear dependence upon stability. The met tower (~1 RD upwind of the second row of turbines) is located at the end of a fairly flat hilltop, beyond which the terrain drops sharply in the direction of the prevailing flow. As the lapse rate goes from unstable to stable, the mean vertical velocity goes from positive to negative. This is a small-scale example of how stability affects the wind flow and is similar to the effect that contributes to the advantageous wind regime in the Altamont Pass.

Standard Deviation of Vertical Velocity

Like the standard deviation of wind speed, there was a consistent increase in the value of this parameter with wind speed. In terms of magnitude, the standard deviation of vertical velocity was on the order of two-thirds of the standard deviation of wind speed. This was true for both sites W8 and W10 for all four conditions analyzed. Hence, the relative increases in this turbulent component due to turbine wake influences were of the same order as those observed with the standard deviation of wind speed (or turbulence intensity). The increases under unstable conditions are observed to be greater than those for Ti, but they are almost identical for stable conditions. Table 2 shows the results of this analysis.

Similar to turbulence intensity, the magnitudes of the standard deviation of vertical velocity were lower during stable periods than when unstable conditions prevail, although the difference between them is slight.

TABLE 2. COMPARISON OF STANDARD DEVIATION OF VERTICAL VELOCITY (CM/SEC) AT SITES W8 AND W10.
WIND SPEED RANGE = 9.0 TO 12.5 M/S.
MEAN WIND SPEED = 10.5 M/S.

	Unstable		Stable	
	W8	W10	W8	W10
No Wake	78	74	76	67
Wake	110	104	109	96
		Change		
Wake/No Wake	51%	40%	43%	44%

WIND SPEED ANALYSIS

The analysis of wind speed conditions is important from the standpoint of energy capture by turbines operating in the wake of other turbines. As it turns out, the inclusion of the stability measurements makes a significant difference in explaining the observed results. In this portion of the study, and in the remaining portions, the wind speed measured at the upwind location, W1, is used as the wind speed reference, as wind speed deficits must be considered with respect to some unaffected site.

Wind speed deficits are defined here as the percent change in mean wind speed, due to turbine wakes, at the downwind location. The mean speed at W1 was the same for all four conditions. As an additional way of ensuring equal wind input to the system, and thus a consistent basis for comparison, the range of wind speeds used at W1 was selected so that the mean square of the wind speeds (the mean "energy") was the same for all cases, as well as the mean speed.

TABLE 3. COMPARISON OF MEAN WIND SPEEDS (M/S)
AT SITES W8 AND W10.
SITE W1 WIND SPEED RANGE = 8.8 TO 12.5 M/S.
SITE W1 MEAN SPEED = 10.5 M/S

	Unstable		Stable	
	W8	W10	W8	W10
No Wake	10.1	10.4	10.3	10.4
Wake	9.7	10.3	9.6	9.8
		Change		
Wake/No Wake	-5%	-1%	-7%	-5%

These results are consistent with what one might expect, although the magnitudes of the velocity deficits may not be consistent with model results. Nonetheless, the deficits are greater at site W8 than at site W10 and are greater at both sites in the stable situation.

In contrast to the analysis of Ti versus wind speed, a graphic display of the relationship between the wind speeds at sites W1 and W8 and W10 does not show the same regular patterns observed in the plot of Ti versus wind speed discussed earlier. Plotting wind speed ratios (site W8/W1 and W10/W1) versus W1 wind speed shows some unexpected variability in the wake and non-wake conditions.

With an unstable boundary layer, both sites show large velocity deficits at speeds (at W1) below ~10 m/s, at which turbine thrust coefficients are highest. Above that speed, site W10 shows no deficits and even velocity increases over the range of speeds from ~10 to ~11 m/s. Site W8 maintains consistent velocity deficits of ~3 to 4% at speeds above 10 m/s.

In the stable case, wind speed ratios at both sites show fairly well behaved patterns, that is, velocity deficits thoughout the range of wind speed measured. There is an exception, though, and again that is site W10. Here, at speeds from ~12.5 to ~14 m/s velocity increases are shown, ie. wind speed ratios greater than those calculated with no turbine wakes present. The most probable cause for this phenomenon has been identified.

This is that due to the upwind turbine configuration, some free-stream air may be mixing with the wake flow from the side. In the upwind string of turbines, there is a break of approximately 3 RD where no turbine had been sited due to terrain considerations. Free-stream air coming through this gap could help restore the momentum. When data analysis is restricted to records with wind directions in a range which would not allow this possibilty, a different result is obtained.

In this subset of data, quite unexpectedly, the non-wake and unstable/with wakes conditions show almost identical relationships as before between sites W1, W8 and W10. It is in the stable/with wakes case where the real difference occurs. Whereas in the stable/with wakes case using all data, the wind speed deficits were 7 and 5% at W8 and W10, respectively, they jump to 11% at both sites in the wind direction-restricted subset, as Table 4 shows. As before, the data were selected so that the mean speed and "energy" at site W1 were equal in all four cases.

TABLE 4. COMPARISON OF MEAN WIND SPEEDS (M/S)
AT SITES W8 AND W10. W1 WIND DIRECTION > 240 deg.
SITE W1 WIND SPEED RANGE = 9.2 TO 12.5 M/S.
SITE W1 MEAN SPEED = 10.7 M/S

	Unstable		Stable	
	W8	W10	W8	W10
No Wake	10.3	10.5	10.5	10.4
Wake	9.8	10.5	9.3	9.3
		Change		
Wake/No Wake	-4%	-1%	-11%	-11%

A graph of the wind speed ratios versus wind speed for the restricted data set, unstable conditions, is very similar to that obtained using the original "unstable" data set. The stable case shows striking wind speed deficits which actually increase with wind speed up to ~11 m/s. With a mean speed at W1 of 11.5 m/s, 13 and 12% velocity deficits were calculated at sites W8 and W10, respectively. At speeds greater than 11 m/s, the deficits gradually decrease, but are still substantial at 13 m/s.

A similar analysis of the turbulence data, using the same technique of screening on wind direction, shows only a moderate (5% to 10%) increase in Ti due to turbine wakes, over the values in Table 1, and that only for the stable/with wakes case. Standard deviation of vertical velocity showed essentially no change whatsoever. If intrusion of free flow air into the wake flow is responsible for the variation in wind speed deficits, the mixing processes involved do not reduce the turbulence levels to a significant degree.

TURBINE POWER DEFICITS

Power output was measured from one turbine in the second row which was subject to wake influence due to the upwind string of turbines. Analysis of the effects of those turbine wakes on the power output had a similarity to the results of the wind speed analysis. When all data is used (at least over a consistent range of wind speeds at site W1) the mean power deficits were smaller than when the data were restricted to wind directions which would guarantee full immersion in the upstream wakes.

In fact, in the unstable case, the mean power output of the turbine was greater with wakes present than in their absence. This could be due to changes in wind shear observed in the waked condition. This aspect of the tests will be discussed in the next section. Table 5 shows the results of the mean power analysis.

When the wind direction restriction is applied, the mean power losses in the stable condition increase, similar to what was observed with the wind speed deficits.

TABLE 5. COMPARISON OF MEAN TURBINE POWER (KW).
SITE W1 WIND SPEED RANGE = 8.9 TO 12.1 M/S.
SITE W1 MEAN SPEED = 10.5 M/S

	Unstable	Stable
No Wake	235	249
Wake	247	223
	Change	
Wake/No Wake	5.3%	-10.4%

SITE W1 WIND SPEED RANGE = 8.7 TO 12.8 M/S.
SITE W1 MEAN SPEED = 10.4 M/S.
SITE W1 WIND DIRECTION > 240 DEG.

	Unstable	Stable
No Wake	238	248
Wake	241	216
	Change	
Wake/No Wake	1.2%	-13.0%

The power analysis shows further agreement with the wind speed. Recall that in the wind direction-restricted, stable/with wakes case, the wind speed deficits were reported to increase as wind speed (at W1) increased. Similarly, for a power data set with the same range of wind directions, power losses continue to rise with W1 wind speed. For a range of speeds from 9.2 to 14.3 m/s (mean wind speed = 11.6 m/s) the mean power with no wakes was 287 kW. The mean power with wakes was 244 kW, which represents a 15% loss.

The power losses show up clearly in a power curve using W1 wind speed as the reference. In all cases, except stable/with wakes, the curve equals or exceeds the theoretical power curve. The curve in the stable/with wakes starts to show a deficit at a wind speed of around 10 m/s. At speeds of 14 m/s and greater, the power deficits were not evident. The curves are much the same when the data is screened by wind direction, with the exception that the power deficits in the stable/with wakes case are much more severe and extend over a wider range of wind speeds. In this case, the power deficit persisted beyond 14 m/s, with maximum power losses occurring in the 11 to 12.5 m/s speed range.

These results have important implications regarding the applicablility of wake test results in the Altamont Pass to other parts of the world. For some time it had been observed by numerous investigators that wake energy losses were much higher in the Altamont Pass than had been expected or modeled. This apparently can be explained, to a large degree, by the strong dependence upon static stability. Stable lapse rates occur frequently in the Altamont, particularly at night when the wind speeds are at their highest. These results tend to validate the work done in Europe (less stable boundary layer) prior to the large-scale development of turbines in California.

Another factor which should not be overlooked, however, is effects due to terrain. The area used for this study is, nominally, a flat terrain location. In situations where elevations decrease downstream, wake energy losses could be greater than those measured here.

As is seen here in Tables 4 and 5, both wind speed and turbine mean power deficits are negligible at a distance of 10 to 11 RD under unstable conditions. Under stable conditions, both show dramatic increases in magnitude. Although the power data presented here is from only one turbine and not an entire string, it is felt to be representative of what would occur in an entire string of turbines subjected to the same kinds of conditions measured here.

VERTICAL WIND SHEAR

At site W8 wind speeds were measured at levels of 14m, 24m (hub height), and 40m (rotor top). The mean speeds measured at these locations allowed the analysis of variations in wind shear due to the presence of turbine wakes. The data from these levels were grouped according to stability and wake condition as were the other data, and from the mean speeds at each height the vertical wind shear exponent, alpha (α), was calculated between levels. Changes in α from non-wake to waked conditions were then analyzed. The results are presented in Table 6.

The data in Table 6 show that wind speed deficits due to wakes tend to be more extreme below hub height than above. This is evidenced by the fact that the changes in wind shear exponents were toward higher positive values. Whatever decrease in wind speed may be experienced at hub height, the losses at lower levels were proportionally greater. Likewise, the deficits measured at hub height are greater than those at the height of the top of the rotor.

There is a consistency between the wind shear measurements and the turbine power data discussed above. The reader may have noticed in Table 5 that in the unstable case, the mean power increased with turbine wakes present over the non-wake value. Assuming that the wind shear measured at site W8 is representative of the wind shear at W10, adjacent to the turbine, this observed power increase could be explained to a certain extent by a change in wind shear. The mean wind speed actually increased at the upper level with turbine wakes present.

The difference in wind speeds at the various levels in the stable/no wake and the unstable/no wake conditions is consistent with the difference in mean power measured under the two conditions. Also, the wind speeds and mean power in the stable/wake case were the lowest of all.

TABLE 6. COMPARISON OF MEAN WIND SPEEDS (M/S) AT 14, 24 and 40 METER ELEVATIONS AT SITE W1.
SITE W1 WIND SPEED RANGE = 9.2 TO 11.9 M/S.
SITE W1 MEAN SPEED = 10.4 M/S

MEAN WIND SPEEDS (M/S) *

	Unstable			Stable		
Level	14m	24m	40m	14m	24m	40m
No Wake	9.1	9.6	10.0	9.5	10.0	10.7
Wake	9.0	9.5	10.3	8.8	9.3	10.2

WIND SHEAR EXPONENT (α)

	Unstable		Stable	
Shear Level	14-24m	24-40m	14-24m	24-40m
No Wake	0.09	0.09	0.09	0.14
Wake	0.09	0.17	0.10	0.20
	Change in Alpha **			
Wake/No Wake	10%	84%	14%	44%

* Wind speeds measured with the Maximum Cups were ~4% lower than with the R. M. Young propvane at the same location.

** Values of α used in these calculations were not rounded.

One might well ask what has become of the highly vaunted and much ballyhooed Altamont Pass negative wind shear in these measurements? Historically, it was quite common to see negative shears in all areas of the Altamont. In this study, negative shears were rather infrequent and observed mostly with highly stable lapse rates. They have been consumed in the averaging process and their presence all but covered up. This is apparently aided by wake effects which could persist beyond a wind turbine project's boundary.

In one particular test, which was run late at night under very stable conditions (the 40m - 10m temperature difference was ~2 deg C), the no-wake wind shear was negative throughout the vertical extent of site W8. When turbine wakes were introduced, the shear pattern completely reversed itself, becoming positive between all levels on the tower. These data are presented in Table 7 below. In all previous analysis, the mean temperature difference between the 40 and 10 meter heights was ~-0.5 deg C in the unstable cases and ~0.4 deg in the stable cases. It is clear that in this particular test the boundary layer was considerably more stable than on the average.

TABLE 7. WIND SHEAR DURING WAKE TEST 1.06.

MEAN WIND SPEEDS (M/S)

Elevation	14m	24m	40m
No Wake	6.3	6.2	6.0
Wake	6.0	6.2	6.5

WIND SHEAR EXPONENT (α)

	14 - 24m	24 - 40m
No Wake	-0.03	-0.06
Wake	0.04	0.08

These results show that the pattern of wake-induced wind speed deficits in the vertical plane contributes heavily to more positive wind shears. The presence of a large installation of wind turbines could alter the vertial wind speed profile for a considerable distance downwind.

SUMMARY

The results of this analysis regarding turbine wake effects and stability can be briefly summarized.

At 10 RD downwind from a line of turbines, increases in turbulence intensity (or standard deviation of wind speed) of 25 to 40% were measured for unstable and stable boundary layers, respectively. Although relative increases in turbulence were greater in the stable case, the absolute turbulence levels were lower. Percent increases in standard deviation of vertical velocity were larger than those in Ti for the unstable case and the same in the stable case. Similarly, absolute turbulence magnitudes were lower with stable conditions than with the unstable.

Wind speed deficits due to turbine wakes increase as the stability increases. In unstable conditions, the speed deficits at 10 RD were negligible. In stable conditions the deficits increased to 5%. In the "total immersion" situation (with the met towers completely within the wake boundary, with greatly reduced free-stream air mixing in from the sides), the speed defifcts jumped to 11% in stable conditions and remained near 0% in the unstable case. Wind speed deficits continued to increase with wind speed up to ~11 m/s under these same circumstances. "Total immersion" did not have a significant effect on turbulence levels.

Turbine power measurements in the four classifications studied, showed more variability than could be explained by the 10 RD wind speed alone. In the unstable case, mean power increased by 5% when wakes were introduced. In the stable case, the mean power decreased by 10% because of wake effects. With total immersion and unstable conditions, the mean power was essentially unchanged when wakes were present. However, in the stable case, mean power dropped by 13% with the addition of turbine wakes. Maximum power deficits occurred at a mean speed of ~11.5 m/s.

Wind turbine wakes appear to affect the lower level winds more profoundly than the upper (top of the rotor) winds, causing the wind shear exponents to become more positive. In the unstable case, wind speed deficits at the lower levels were accompanied by an increase in wind speed at the top. Under stable conditions, wind speed deficits were observed at all levels, the lower levels suffering greater deficits than the top. Turbine wake influences were observed to cause the vertical shear profile to be inverted from negative to positive shear under highly stable conditions.

CONCLUSIONS

The inclusion of the static stability measurement has proved to be an important factor in the analysis of the various parameters measured in this series of wake tests. Many will find solace in the fact that wake energy losses are greatly reduced (if not completely eliminated) at 10 RD with unstable conditions, which are more prevalent elsewhere than in the Altamont Pass. Some caution should be exercised in applying these results, as they were derived from tests involving only two rows of turbines in essentially flat terrain and may not hold true if extrapolated to many rows of turbines in complex terrain.

Nonetheless, the results of the turbine power portion of the analysis tend to validate the assumptions that were used in much of the siting work early-on in the development of the Altamont Pass and other areas of California. Unfortunately, they don't hold up well in the Altamont, due to the high frequency of stable boundary layers. It is worth noting that the role of terrain effects cannot be discounted in assessing potential or existing wake energy deficits. Certain terrain configurations can act to amplify wake energy losses.

While unstable boundary layers are an apparent aid in dissipating turbine wakes, there is a price for that assistance. The downside of having consistently unstable conditions is that turbulence levels, particularly with turbine wakes present, are higher than with stable conditions. However, it may be easier for engineers to deal with higher turbulence than for financiers to deal with higher energy losses.

The bottom line is that it is advisable to get the kind of data necessary to know the wind and atmospheric conditions at a proposed wind turbine park before it is built. Experience is showing that one cannot know too much about one's wind resource.

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