Title
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INTRODUCTION

Wind power production varies on a diurnal and seasonal basis. In this paper, we use wind speed data modeled by TrueWind, Inc., to assess the effects of wind timing on the value of electric power from potential wind farm locations in California and the Pacific Northwest. The intra-annual wind speed variations reported in the TrueWind datasets have not previously been used in published work, however, so we also compare them to a collection of anemometer wind speed measurement and to a limited set of actual wind farm production data.

The research reported in this paper seeks to answer three specific questions:

1) How large of an effect can the temporal variation of wind power have on the value of wind in different wind resource areas?
2) Which locations are affected most positively or negatively by the seasonal and diurnal timing of wind speeds?
3) How compatible are wind resources in the Pacific Northwest and California with wholesale power prices and loads in either region?

The latter question is motivated by the fact that wind power projects in the Pacific Northwest could sell their output into California (and vice versa), and that California has an aggressive renewable energy policy that may ultimately yield such imports.

This paper summarizes results that are presented in more detail in a forthcoming report from Lawrence Berkeley National Laboratory. The full report will be available in summer 2005 at http://eetd.lbl.gov/EA/EMP/re-pubs.html.

METHODS

We used three wind datasets to estimate the time-varying wind power available from California and Pacific Northwest wind sites:

1) TrueWind: TrueWind, Inc., provided modeled wind speeds for every cell on a 200-meter grid in California and a 400-meter grid in the Pacific Northwest. Wind speeds were given for every month-hour combination in California and every season-hour in the Pacific Northwest.
2) Anemometers: We used hourly anemometer data from Kenetech, Inc. (160 sites), the Bonneville Power Administration (6 sites) and the DOE Candidate Site program (7 sites).
3) Actual Wind Farm Production: We used historical hourly power production data from the Altamont, Tehachapi and San Gorgonio areas in California.

We used the wind data with electricity load and wholesale electricity price series for California and the Pacific Northwest to estimate the effects of wind timing on the value of wind-generated electricity at locations throughout California and the Pacific Northwest. The effect of timing was measured by two approaches, yielding three key metrics for each location.

- **Capacity Metric:** We calculated the annual average capacity factor for a wind turbine at each location and then the capacity factor for that turbine during the top 10 percent of historical peak-load hours. The difference between these two capacity factors is a loose proxy for the effect of wind timing on the “capacity value” of a wind turbine at any location.
Price Metrics:  We estimated the annual wholesale market value of a flat block of power and the annual market value expected from the time-varying wind speeds found at each location (when correlated with time-varying wholesale market prices). The difference between these two values reflects the potential effects of temporal wind patterns on the wholesale market value of power from a wind turbine. These values were calculated using (1) historical wholesale power prices, and (2) forecast wholesale power prices.

Historical loads for California and the Northwest were based on FERC Form 714 filings by electric utilities for 2000–03. Historical wholesale prices for California were the average of the CalPX prices for the NP15 and SP15 hubs for 7/98–6/99, and historical prices for the Pacific Northwest were based on the Dow Jones hourly prices for the Mid-C hub for 5/02–12/04. Our forecast price series for California was the average of hourly forecasts for all California hubs for 2006–13, provided by the California Energy Commission. Our price forecast for the Pacific Northwest was the average of the Northwest Power and Conservation Council’s base-case forecasts for the Mid-C hub for the years 2006–2025.

For some of the analysis that follows, we grouped the anemometers in our dataset into separate “wind resource areas,” about 40 km across, in order to estimate the local effects of wind timing in the areas that are most likely to receive wind power development. These areas are shown in Figures 1 and 2.
REGION-WIDE RESULTS FROM TRUEWIND DATA

We found that temporal wind patterns at different locations could have a large effect on the average power output during hours of peak electricity demand, and a smaller but not insignificant effect on the annual wholesale market value of wind power, based on historical and forecast market prices.

Figure 3 summarizes the findings from the TrueWind data for all grid cells in California and the Northwest with annual average winds equivalent to Class 4 or greater. The central bar of each marker in Figure 3 shows the median effect of wind timing on each measure of wind power, based on the TrueWind data. The lower and upper bars show the range of effects between the 10th and 90th percentile of wind sites in each region. It should be noted that these results include many locations that are inaccessible or otherwise unsuitable for wind farm development.

The TrueWind data indicate that the best- and worst-timed of the windy California grid cells have peak-hour capacity factors that range from 6.5 percent above to 32 percent below their annual average capacity factors, with a median of 16 percent below. Windy locations in the Northwest have peak-hour capacity factors ranging from 8 to 40 percent above their annual capacity factors, with a median of 24 percent.

According to the TrueWind data, the best-timed California sites have a wholesale market value approximately equal to what would be obtained if their power output was completely uncorrelated with electricity demand, while the worst-timed sites would have a market value about 4–6 percent less than this, based on historical or forecast prices. The timing of wind at sites in the Pacific Northwest covers a somewhat more negative range than California when forecast prices are used, but yields a wholesale market value ranging from an amount equal to what the wind site would earn with uncorrelated power output, up to about 3 percent more than this, when historical prices are considered.
REGION-WIDE RESULTS FROM ANEMOMETER DATA

Figure 4 shows the range of the three wind value metrics, when using either anemometer measurements or TrueWind data for the cells matching each anemometer tower. Although these findings are not as comprehensive as those shown above, they allow us to compare the results from the TrueWind and anemometer data at similar locations. Anemometers in our dataset are generally concentrated in the most promising areas for wind development, so the results found at these locations may also be more representative of the effects of wind timing in the areas where wind farms are likely to be built.

![Comparison Between Wind-Value Measures Derived from Anemometer Measurements and Measures Derived from TrueWind Data for the Same Locations](image)

The TrueWind data suggest that wind timing generally reduces the value of power at California anemometer sites, while the anemometer data suggest that wind timing raises the value of power at those same locations. This difference appears to be caused by disagreement about the diurnal timing of summer winds in some California wind resource areas, which is discussed further in the next section. Despite this disagreement, the two datasets generally agree on the size of the effect of wind timing (that is, the difference between the best and worst timed sites).

The two datasets are in better agreement in the Pacific Northwest. There, by either measure, wind resources at the anemometer sites appear to be about neutrally matched to historically winter-peaking electrical loads and wholesale market prices, while the wind resources are matched somewhat worse to forecast wholesale market prices that are more summer-peaking.

The TrueWind results for all California Class 4+ grid cells, shown in Figure 3, include summer-peaking coastal and mountain locations that make them more optimistic than the results at the anemometer locations used for Figure 4. Figure 3 also shows better results than Figure 4 for load-weighted capacity factors in the Pacific Northwest, probably because of the inclusion of winter-peaking mountain sites where anemometers have not been placed and wind resource development is unlikely.
TEMPORAL WIND PATTERNS FROM TRUEWIND, ANEMOMETER AND PRODUCTION DATA

Before we present the effects of wind timing in each of the resource areas defined earlier, we briefly compare the wind patterns reported by our three datasets for these areas. We find that there is generally good agreement between the TrueWind and anemometer data about the times of year when wind speeds peak in each resource area. The two datasets are also in reasonably good agreement about winter-time diurnal profiles in each resource area, which tend to be relatively flat. However, in some resource areas, the two datasets show significant disagreement about summertime diurnal wind profiles. These disagreements can in turn cause significant disagreement about the effect of wind timing on the value of power when summer-peaking load or price series are considered. We note three distinct types of disagreement about summer diurnal wind speed profiles:

1) In a number of resource areas, the TrueWind data show a deeper, longer dip in summer daytime wind speeds than the anemometer data, reducing the amount of power available on summer afternoons (Figure 5a). We observed this type of disagreement in four of the twelve Northwestern resource areas (Boardman, Ellensburg, Rattlesnake Ridge, and Vansycle/Kennewick), and four of the nine California resource areas (Solano, Altamont Pass, Romero Overlook and San Gorgonio).

2) In several resource areas, the TrueWind data show summer winds rising steadily from early afternoon until they peak at midnight, while the anemometer data show winds rising from late morning and peaking around 6 pm (Figure 5b). This type of disagreement also causes the TrueWind data to report that less power is available to meet summer-afternoon-peaking electricity loads. We noted this effect in the Ellensburg and Rattlesnake Ridge areas in Washington, and in the Tehachapi, Sidewinder and San Diego areas in California.

3) In the Blackfoot and Livingston areas in Montana and the Mountain Home area in Idaho, the summertime diurnal profiles from TrueWind and the anemometers are nearly reversed (Figure 5c). In these areas, anemometers show morning lulls and afternoon peaks, while the TrueWind data show morning peaks and afternoon lulls, again reducing the amount of wind power available on summer afternoons.

![Figure 5. Diurnal Average Capacity Factor for Three Resource Areas from Anemometers and TrueWind Data at the Same Grid Cell, and Production Turbines in the Same Region](image-url)
The historical production data from operating wind projects in the Tehachapi and San Gorgonio areas appear to agree more with the TrueWind data, while the historical production data for Altamont Pass more closely resemble the anemometer data. However, these comparisons are of limited value in resolving the disagreement between the TrueWind and anemometer data, because the wind turbines in these locations are mounted at relatively low tower heights.

It is possible that the differences in temporal wind speed patterns between the anemometers and TrueWind data are due to temporal variations in wind shear, which reduce power production at higher levels on summer days, relative to other times of day and year. In this case, the TrueWind data (calculated for tower heights of 50 m in the Northwest and 70 m in California) could provide information about upper-level winds that is more accurate than the anemometer data (mostly collected at a height of 20-30 m). The height of the turbines at wind farms in California is often between the anemometer heights and the TrueWind reference height, so the intermediate estimates of the effect of wind timing from the wind farm production data are consistent with this hypothesis. More anemometer or production data from tall towers is needed before we can judge whether this is the case, or say confidently whether the TrueWind data provide an accurate picture of the effect of wind timing on the value of power at most wind resource sites.

EFFECTS OF WIND TIMING IN EACH RESOURCE AREA

In the full version of this report, we show the effects of wind timing using historical electricity loads and historical and forecast prices for both California and the Pacific Northwest, for each of the specified wind resource areas. For brevity, here we discuss only the results found using historical wholesale prices for California and the Pacific Northwest. California’s historical wholesale prices peak on summer afternoons, and the results we find using this series are similar to those found using California’s historical loads or forecast prices, which also peak on summer afternoons. Variations in load-weighted capacity factor are about ten times greater than variations in market value, but the relative standing of different resource areas remains the same. The Northwest’s historical wholesale prices peak on winter mornings and evenings, and this data series yields similar results to those found using the Northwest’s historical electricity loads. The Northwest’s forecast wholesale prices are summer-peaking, however, and the results found using that series are similar to the results shown here using California’s historical prices, and dissimilar to those shown for the Northwest’s historical prices.

Figure 6 shows the effect of wind timing on the wholesale value of power at all grid cells in California and the Northwest, as estimated using the TrueWind dataset, with California’s historical market prices. Figure 7 shows the same information, but uses the Pacific Northwest’s historical market prices instead of California’s. From the TrueWind data, it appears that winds at most locations in California and the Northwest are better matched to the Northwest’s winter-peaking historical prices than to California’s summer-peaking prices. It is important to note, however, that most of the areas shown in these maps are unsuitable for wind farm development, due to low winds, poor accessibility or other factors. In the areas that are suitable for development, the effects of timing may differ from the state-wide pattern. We also note that the anemometer data discussed below show a somewhat better match to California prices than the TrueWind data shown here.
Figure 6. Percentage Change in Market Value of Power due to Temporal Wind Patterns, Using TrueWind Wind Data and Historical California Power Prices

Figure 7. Percentage Change in Market Value of Power due to Temporal Wind Patterns, Using TrueWind Wind Data and Historical Pacific Northwest Power Prices
In Figure 8, we show the effects of wind timing on the value of wind power from each of the resource areas where anemometers were placed, when considering historical California wholesale power prices. The red and blue markers indicate the median effects among all anemometer locations in each resource area, as calculated using either anemometer data or TrueWind data at the same sites. For the Altamont, Tehachapi and San Gorgonio resource areas, we also show the effects calculated using the total output from all wind farms in each region. California’s historical wholesale power prices peak strongly on summer afternoons. Consequently, the TrueWind and anemometer data show significant disagreement about the effects of wind timing in the same places where they disagree about summer afternoon wind speeds, particularly including California’s major existing wind resource areas. Where available, the actual historical power production data yield results that are intermediate between those found using the other two datasets.

According to the anemometer data shown in Figure 8, about half of the Northwestern resource areas and two-thirds of the California resource areas are positively matched to California’s summer-afternoon-peaking historical prices. However, TrueWind data at the same locations suggests that only a quarter of the Northwestern resource areas and no California areas are positively matched to California’s historical prices. If both the anemometer and TrueWind data are correct, and the differences are due to their different elevations, then it is possible that the timing of power production will worsen as new wind farms use taller towers, offsetting some of the gains due to improved capacity factors.

Figure 9 shows the effects of temporal wind patterns on the value of wind power from each resource area, using the Northwest’s winter-peaking historical wholesale prices. Values calculated using this price series are much less sensitive to summer daytime wind speeds, so there is good agreement between the anemometer and TrueWind datasets. Seven out of twelve...
Northwestern resource areas appear to be at least somewhat positively matched to historical Northwestern wholesale prices, while only one of the nine California sites shows a clear positive match.

![Figure 9. Median Effects of Timing on Market Value at Anemometer Sites in Each Resource Area, Based on Historical Northwestern Prices](image)

**DATA LIMITATIONS**

Several factors may reduce the accuracy of our estimates of turbine-height wind speeds from the TrueWind, anemometer and production datasets. These factors could reduce the quality of fit between the datasets, and make it difficult to say which dataset gives a more accurate picture of hub-height wind patterns.

- **Modeling Uncertainty.** The TrueWind wind-speed estimates and diurnal profiles are based on a computerized atmospheric model, which is subject to uncertainty due to limitations in its resolution and the number of atmospheric processes it can incorporate.

- **Wind Shear.** We estimated wind speeds at a 70 m hub height from anemometer measurements taken at lower elevations by way of a simple power law relationship, with a fixed exponent (1/7) at all times and locations. This approximation neglects the fact that wind shear can change with time and terrain. We also applied no correction to the available wind farm production data, which came from a variety of heights.

- **Limitations of Historical Data.** TrueWind worked to ensure that their wind speed estimates reflect a “typical meteorological year.” However, our anemometer and wind farm production data come from several different years, and cover differing lengths of time at each site, so they may not represent typical meteorological conditions. This problem is reduced by the fact that we use only month-hour or season-hour averages of wind data for our analysis.
• **Anemometer Location.** The locations reported for anemometers in our dataset may be incorrect by a few kilometers in some cases, causing them to be compared to the wrong TrueWind grid cell.

• **Effective Ground Level Differences.** The wind speeds reported by TrueWind were given at heights of 50 or 70 meters above “effective ground level.” In dense forest, this is relative to the canopy height, which may be a significant distance above the true ground level. We did not correct these effective heights to true heights before comparing them to observations.

**CONCLUSIONS**

**Temporal patterns have a moderate impact on the wholesale market value of wind power and a larger impact on the capacity factor during peak hours:** Whether using historical or forecast Northwest or California prices, the best-timed wind power sites have a wholesale market value that is up to 5–10 percent higher than the value of a flat baseload block of power (i.e., the average market price). The worst-timed sites have a market value that is up to 10 percent below a flat block of power. Assuming an average wholesale price of $50/MWh, the best-timed sites may have a wholesale value that is as much as $7.5/MWh higher than the worst-timed sites. Temporal wind patterns could have a greater impact on the power output from wind farms during the top 10 percent of peak hours of electrical demand, a loose proxy for the “capacity value” of a wind farm. The best-timed wind sites could produce as much as 40–60 percent more power during peak hours than they do on average during the year, while the worst-timed sites may produce 30–60 percent less power during peak hours.

**Northwestern wind appears well matched to Northwestern markets, but California results are mixed:** Both the modeled TrueWind data and the anemometer data indicate that many Northwestern wind sites are reasonably well-matched to the Northwest’s historically winter-peaking wholesale electricity prices and loads, while most California sites are poorly matched to these prices and loads. However, the TrueWind data indicate that most California and Northwestern wind sites are poorly matched to California’s summer-afternoon-peaking prices and loads, while the anemometer data suggest that many of these same sites are well matched to California’s wholesale prices and loads. Actual production data from California’s three major wind resource areas yield results that fall between those from the TrueWind and anemometer data.

**TrueWind and anemometer data disagree about California’s summer afternoon wind speeds:** The TrueWind data indicate that wind speeds at sites in California’s coastal mountains and some Northwestern locations dip deeply during summer days and stay low through much of the afternoon. In contrast, the anemometer data indicate that winds at these sites begin to rise during the afternoon and are relatively strong when power is needed most. At other times and locations, the two datasets show good agreement. This disagreement may be due to time-varying wind shear between the anemometer heights (20-25m) and the TrueWind reference height (50m or 70m). Because of this disagreement, the two datasets also differ when estimating the wholesale value of power using prices that peak on summer afternoons (e.g., historical California prices), while they agree about the wholesale value of power when using prices that peak at other times (e.g., historical Northwestern prices).