PREDICTION OF POWER OUTPUT FROM WIND FARM USING LOCAL METEOROLOGICAL ANALYSIS

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ABSTRACT: We have developed a method based on the Local Circulation Assessment and Prediction System (LOCALS) for predicting the power output of wind turbines by using local meteorological data. This method can accurately predict wind energy in order to provide optimum power supply scheduling for balancing energy supply and demand. LOCALS can predict wind speed and power output over a spatial grid area of approximately 500 m or 3 km. The prediction model was applied to TAPPI Wind Park in Aomori Prefecture, Japan, where the wind turbines are located on complex terrain. Although the effect of turbulent wind on the accuracy of wind speed prediction cannot be neglected, the hourly power output predicted by LOCALS agrees well with the measured output; namely, the correlation coefficient is 0.73, BIAS is + 160 kW (about +5.6 percent of the rated power output), RMSE is 434 kW (about 15 percent of the rated power output). This paper outlines LOCALS and discusses the accuracy of its prediction.
Keywords: Forecasting Methods, Forecasts, Terrain

1 INTRODUCTION

There are strong demands around the world to add wind energy to the power generation systems used by utilities, and much attention is being paid to the reliability of techniques for predicting wind energy. In Japan in particular, schedulers of conventional power supplies will have to predict the fluctuation and intermittence of wind energy in order to ensure the correct frequency and voltage of electrical output. Compared to those in Europe, the electrical grid in Japan is not robust enough to allow wind energy to fluctuate excessively without specific measures to handle such fluctuation. Therefore, fluctuating power from wind turbines must be supplemented by conventional power plants that are speed-governed or under the output control that is correctly scheduled in advance with the method for predicting wind energy.

Although several prediction models have been suggested[1-3], there have been very few attempts to apply them at sites in Japan. In Europe and the U.S.A., wind turbines are usually built on fairly flat terrain. In Japan, however, it is not unusual for wind turbines to be located on complex terrain, because of the limited amount of land available for them and the many regulations concerning land use.

LOCALS (Local Circulation Assessment and Prediction System) is a state-of-the-art numerical atmospheric phenomenon prediction model. It has been improved to forecast localized wind speed and power output from wind farms. In the current study, we applied LOCALS to a site where the wind turbines are located on complex terrain.

2 METHODOLOGY

2.1 Wind farm

The prediction was carried out at TAPPI Wind Park in Aomori Prefecture, Japan. This site has ten wind turbines producing a rated gross power capacity of 2,875 kW. Figure 1 is a bird's-eye view of the complex terrain of this site, shown in detail by the contour map in Figure 2.

Figure 1: A bird's eye view of TAPPI Wind Park. There are sheer cliffs down to the sea and the turbines are built on a steep mountain side.

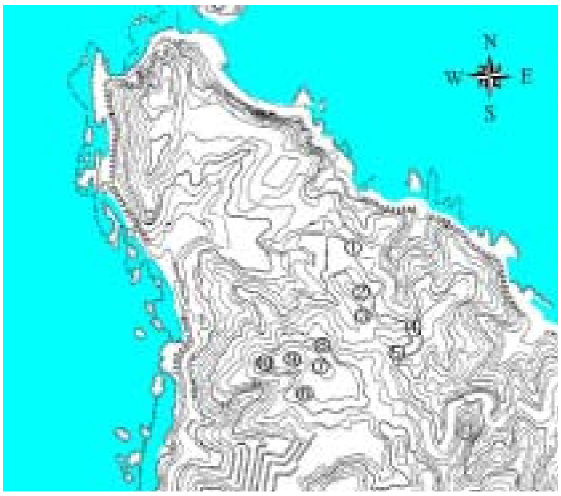

Figure 2: Contour map of TAPPI Wind Park. Encircled numbers ①-⑩ indicate the turbine locations.

This site sometimes experiences unusually turbulent wind, which is caused by an interruption of the wind stream by the topographic features and the frequent changes in surface roughness. The main specifications of the wind turbines are listed in Table 1.

Table 1: Main specifications of the wind turbines at the TAPPI Wind Park.

Wind turbine	Units 1-5	Units 6-10
Turbine type	Horizontal axis propeller	
Orientation	Upwind	
Generator type	Induction generator	
Rated power	275 kW	300 kW
Rotor height	30.0 m	
Rotor diameter	28.0 m	29.0 m
Rotor speed	43 rpm	
Cut-in wind speed	5.5 m/s	
Rated wind speed	13.0 m/s	14.5 m/s
Cut-out wind speed	24.0 m/s	
Power regulation	Blade pitch control	
Direction alignment	Yaw gear control	

2.2 Prediction method

A schematic diagram of the concept of LOCALS is shown in Figure 3. The hourly surface data and three-hourly aerological data of weather conditions calculated by the Regional Spectral Model (RSM), which is the numerical weather prediction model of the Japan Meteorological Agency, are used as initial and boundary condition data. Although RSM is a well-established model for weather forecasting in Japan, it does not fully represent local meteorology because of its coarse grid (approx. 20-km square). In contrast, LOCALS can predict wind speed in a grid approx. 500-m or 3-km square by using local meteorological data.

The basic equations of LOCALS are based on those given in previous reports[4, 5]. LOCALS can predict localized wind speed by calculating the localized heat balance and water balance, which are determined from fluid dynamics and thermodynamic equations, taking account of localized topographic features, land-use variation, and the relative roughness of the sites. Digital maps and detailed digital information regarding 10-m grid land use issued by the Geographic Survey Institute, an organization affiliated with the Ministry of Construction, provide the above data. Such data, covering all of Japan, have recently become commercially available on CD-ROM. Even if such digital data cannot be obtained in other countries, hand drawings or printed maps can be imported into LOCALS. Power output is predicted from the calculated wind speed and the power curves of the wind turbines.

Since RSM provides real-time weather prediction, and its data can be periodically sent via private telecommunication lines, the initial and boundary conditions can be updated at least once a day, and predictions can be made in hourly steps up to 24 hours from the initialization time at 21:00 Japan Standard Time. The results from LOCALS are usually available within seven or eight hours from the start of the calculation.

LOCALS offers a choice of two spatial resolutions, 500 m or 3 km, as mentioned above. Currently, the finer spatial resolution can take into account more localized conditions, such as variations in terrain, surface roughness, or other parameters. However, when the spatial resolution reaches a certain value (we have tried the prediction with a grid of 50 m) at which the vertical wind cannot be ignored, the time for the three-dimensional calculation becomes extremely long (perhaps 20 or 30 times longer). This means that too fine a spatial resolution is not practical for the daily predictions of electricity utility schedulers. We found a 500-m grid to be suitable for prediction with an ordinary personal computer.

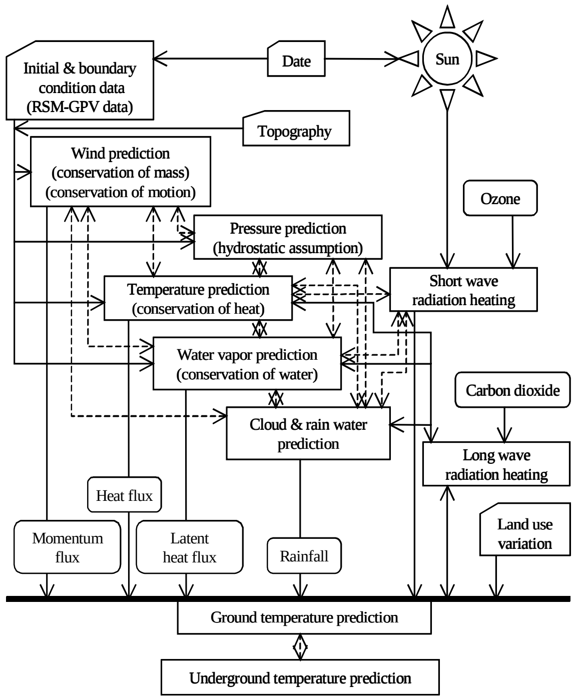

Figure 3: Conceptional diagram of LOCALS. (The arrows indicate interaction of meteorological elements; the basic equations are coupled in accordance with the arrows.)

3 RESULTS AND DISCUSSION

3.1 Wind speed

The wind-speed prediction was carried out over two consecutive months, May 1st to June 30th, 1999.

Scatter plots of predicted vs. measured wind speed are shown in Figure 4. The predicted wind speeds are for a 3-km grid and the measured wind speeds are arithmetical averages of data measured by the anemometer set on each nacelle of units 1 to 10. The predicted wind speeds agree well with the measured data. From this figure, we determined that LOCALS has a correlation coefficient of 0.80, mean error (BIAS) of -0.54 m/s, and root mean square error (RMSE) of 3.3 m/s.

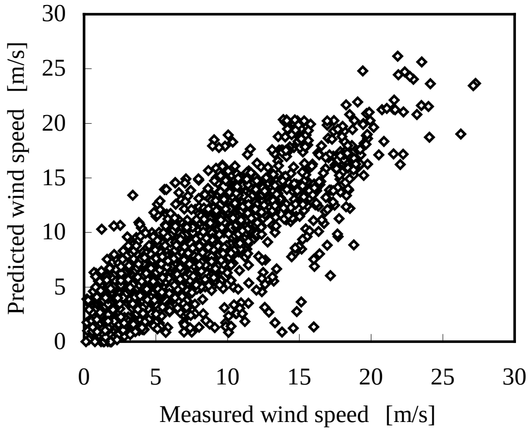

Figure 4: Scatter plots of predicted (3-km grid) vs. measured wind speed

The initial and boundary conditions for the 500-m-grid prediction are obtained from the 3-km grid results. Table 2 lists the main statistical parameters regarding the predicted and measured wind speed at each wind-turbine unit. The accuracy of each prediction varies considerably, with unit 3 having the worst correlation coefficient and unit 4 having the worst BIAS and RMSE. Units 6 to 10 agree fairly well with the respective observed data.

Table 2: Main statistical parameters regarding the predicted (500-m grid) and measured wind speed at each wind-turbine unit.

Unit no.	Correlation coefficient	BIAS [m/s]	RMSE [m/s]
1	0.77	-0.43	2.84
2	0.71	0.67	2.69
3	0.65	0.39	2.19
4	0.72	2.19	4.42
5	0.79	0.80	2.77
6	0.81	-1.72	3.61
7	0.87	0.44	2.88
8	0.82	-0.97	3.14
9	0.88	0.66	3.46
10	0.88	0.40	3.25

3.2 Power spectrum density of wind speed

When the fluctuation period of power output from wind farms is about less than one hour, the speed governing operation of a conventional power plants can handle such a power fluctuation and maintain the appropriate frequency and voltage of the overall electrical power output. If the fluctuation period is more than one hour, however, the overall power output can no longer be maintained. In such a case, the scheduling of power output from the conventional power plants must be able to compensate for fluctuations in wind power output. To enable such compensation, LOCALS is used to accurately predict the fluctuations in wind power output. In the following, Fourier analysis is used to determine the minimum period of wind power fluctuation that LOCALS can handle.

Figure 5 shows scatter plots of predicted (by LOCALS) and measured power spectrum density of wind speed under two conditions: when the fluctuation period of wind speed is (1) more than one hour and (2) less than one hour. It is clear that the predicted power spectrum density agrees well with the measured one when the fluctuation period is more than one hour (correlation coefficient: 0.87); however, when the fluctuation period is less than one hour, the agreement deteriorates (correlation coefficient: 0.40). This result means that the period of wind energy fluctuation that LOCALS can handle is one hour or more. Moreover, to improve the accuracy of the prediction for the fluctuation period of less than one hour, it is planned to incorporate a Kalman Filter (a statistical treatment) into the LOCALS model.

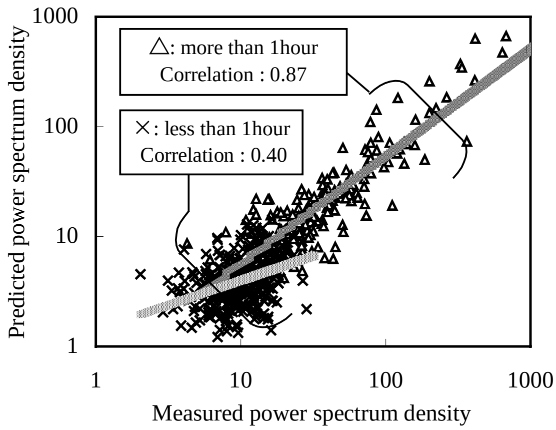

Figure 5: Scatter plots of predicted and measured power spectrum density of wind speed (the broad, gray lines are the best linear fits).

3.3 Turbulence intensity

Figure 6 shows the turbulence intensity, which is the standard deviation of the wind speed measured at 0.5-second sampling intervals over ten minutes divided by a ten-minute time-average of the measured wind speed, against measured wind speed averaged by the method of Bins (Bin width=1.0 m/s) [6].

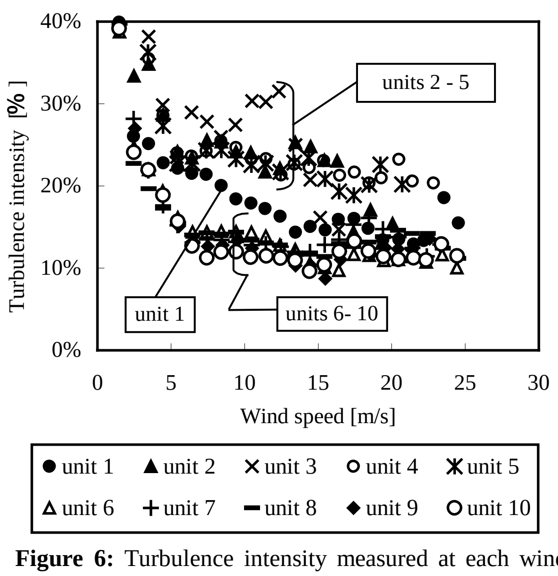

Figure 6: Turbulence intensity measured at each wind turbine unit.

At units 2 to 5, especially unit 3 (which has the worst correlation coefficient in Table 2, i.e., 0.65), the turbulence intensities are much lager than those at units 6 to 10, which have a correlation coefficient of greater than 0.80. These results suggest that greater turbulence is one reason for the lower correlation coefficient. Because of the geographical conditions at which wind turbines in Japan are located, LOCALS will have to be modified to account for predicting unusually turbulent wind.

3.4 Power output prediction results

From the 500-m-grid predicted wind speed and the power curves corresponding to each wind turbine, we can predict the power output. Figure 7 shows a typical comparison time series of predicted (by LOCALS) and measured power output from TAPPI Wind Park. No adjustments or statistical procedures were applied to the measured data. The correlation coefficient of the two sets of data (for the hourly power output from the site) is 0.73, BIAS is +160 kW (about +5.6 percent of the rated power output), and RMSE is 434 kW (about 15 percent of the rated power output). Therefore, it is clear that the predicted data represents the measured data quite closely over the period shown in the figure. These results clearly indicate that LOCALS can be applied to a site where the wind turbines are located on complex terrain, such as TAPPI Wind Park.

In Figure 7, the lack of measured data around June 24th to 25th is due to a manual shut-down because of a storm. Wind turbines sometimes have to be stopped for such cut-offs, maintenance or short-term inspections. The prediction model may require a probability procedure or nonlinear analysis to account for such shut-down events. If the model ignores shut-down events that affect a large number of wind turbines, there might be a detrimental effect on the running and control of the electrical grid and conventional power plants.

As described above, the accuracy of the 500-m-grid wind speed prediction varies according to the location of the wind turbine unit, but the predicted gross power output from the site agrees well with the measured output. The reason for this discrepancy is explained by weather models calculating representative wind speed in simulation areas. It has been reported that the scatter of prediction results is clearly less when the prediction area covers six sites rather than one[3]. It is also possible that the spatial distribution of the wind turbines at the site might reduce the prediction error.

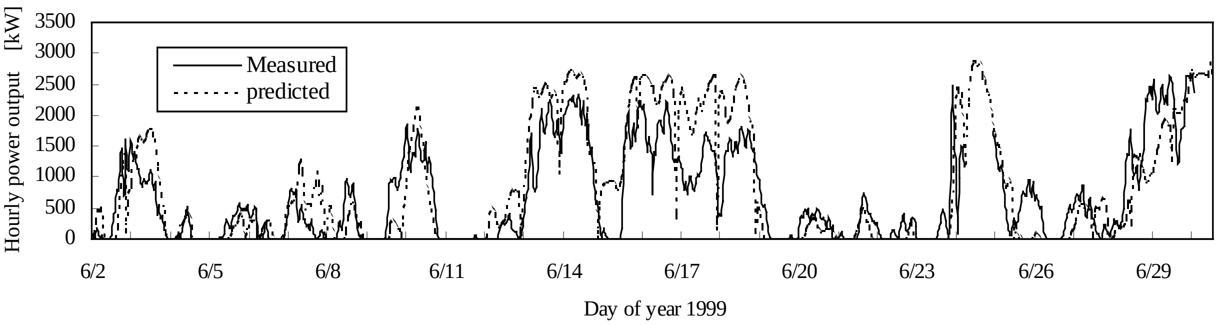

Figure 7: Typical comparison time series of predicted and measured power output in June 1999.

4 FURTHER WORK

We have already started using the Kalman Filter as a solvable method for improving the accuracy of turbulent wind prediction. The LOCALS-based routine prediction will be made available to electrical utility schedulers by this summer.

5 CONCLUSIONS

A model, called LOCALS for predicting the power output from wind farms using local meteorological analysis was developed. The prediction was carried out at TAPPI Wind Park in Aomori Prefecture, Japan, where the wind turbines are located on complex terrain. Although the effect of turbulent wind on the prediction accuracy cannot be neglected, the hourly power output predicted by LOCALS agrees well with the measured output, correlation coefficient is 0.73, BIAS is + 160 kW, and RMSE is 434 kW. Furthermore, we found that the accuracy of the prediction model can be improved by taking the spatial distribution of the wind turbines into consideration.

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