Optimum Locational Allocation of Wind Turbine Capacity based on Smoothing Effect

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Summary

Though it is evident that hourly power generation from a wind turbine varies largely at a single site, the variability in power generation is expected to be reduced due to a smoothing effect when wind turbines are installed at multiple sites.

This study evaluated the smoothing effect of wind turbines based on the hourly power generation converted from wind speed data at five sites in Aomori prefecture in Japan for the past four years with assumptions on a theoretical wind turbine operation mode.

The smoothing effect can be maximized by optimally allocating wind power generation capacity among sites. The standard deviation of hourly variation of wind power generation output at the five sites ranges from 27 to 49W/m^2/h. The study shows that the standard deviation of the superposed power generation hourly variation is reduced to 19W/m^2/h by optimization. Additional improvement in standard deviation by optimization compared with equal allocation among the five sites is not remarkable. Nevertheless, locational allocation is not considered in the actual construction of wind turbines and region-total power output hourly variation may not be reduced. Therefore, a wind power development plan taking into account locational allocation can be one of the measures to enhance integration of wind power plants minimizing negative impact on the power grid systems. However, optimized power output hourly variation of wind turbines is still larger than that of electric power demand.

Assuming a maximum permissible value for the standard deviation of wind power output hourly variation as a threshold of the impact on the current power grid system, this study observed a case where the smoothing effect among five sites allows twice as many wind turbines to be integrated compared to a single site construction. In reality, however, wind turbines are not abundantly installed in sites with good wind conditions, nor dispersed among sites. Analyses selecting the sites where the wind turbines were installed are challenges to be addressed. In addition, although this study focused on comparative analysis of standard deviation among sites, analyses of the absolute value of power generation from wind turbines taking into account the electric power demand should also be addressed.

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Introduction

Although extensive deployment of renewable energy is of great importance in terms of energy security and global warming prevention, there are concerns about negative impacts that variability and intermittency of power generation from wind turbines or photovoltaic might have on the power grid system. It is evident that hourly power generation from a wind turbine fluctuates largely if wind turbines are constructed on a single site. However, the variability in power generation is expected to be reduced due to the smoothing effect when wind turbines are installed in multiple sites.

How much smoothing effect can be expected presumably depends largely on the combination of sites and the power generation capacity to be specified. The smoothing effect also may vary from year to year, depending on the wind conditions.

This study evaluates the smoothing effect of wind turbines for five sites in Aomori prefecture, using the wind turbine hourly power generation data converted from wind speed data of the past four years. In addition, the smoothing effect will be quantified by optimizing locational allocation of wind turbine output capacity.

1. Wind Conditions at the Sites Analyzed

The hourly data of wind speed and wind direction at the five sites in Aomori prefecture from 2009 to 2012 were collected from AMeDAS (Automated Meteorological Data Acquisition System) of the Japan Meteorological Agency. The sites were selected with the criteria that the wind speed should be observed at an observatory and that the wind conditions should be relatively favorable. The wind energy potential map [1] was referred to in selecting the sites. In addition, the sites should be geographically dispersed.

1-1 Adjustment of Wind Speed

The height of the anemometer from ground level varies from each observatory. The equation below [2] is used to estimate the wind speed at the height of the wind turbine to be constructed. This study assumes that the height of the hub is 60m and the diameter of the rotor is 60m. The rated power generation capacity of this size of wind turbine is generally 1,000kW.

$$V = V_0 \left(\frac{h}{h_0} \right)^{1/n}$$

h_0 is the height of the anemometer at the observatory, h is 60m, V_0 is the observed wind speed, V is the wind speed at 60m high and n is a coefficient that describes the features of the land surface. n is empirically specified and varies from 2 to 10 according to prairie, coast, pastoral, urban area, etc. This study assumes 8 for all of the sites selected, as the selected sites are mostly located on coasts.

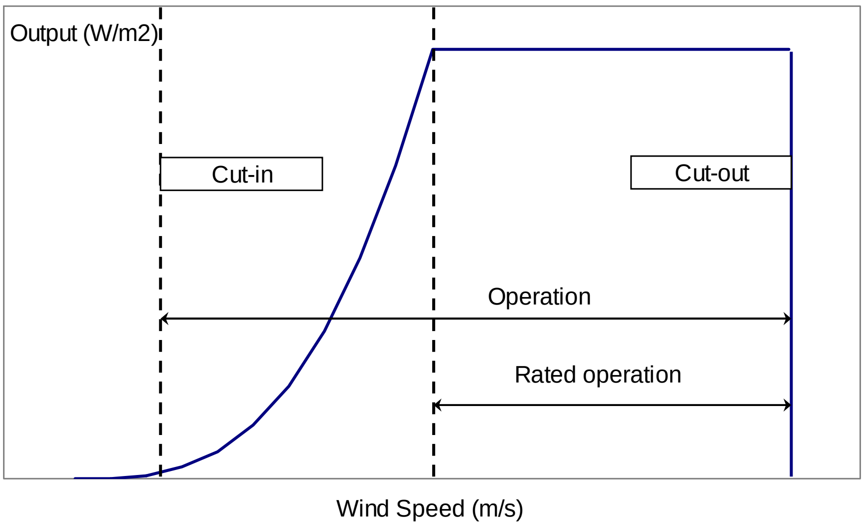
1-2 Estimation of Wind Turbine Power Generation

Wind turbines operate from a wind speed that makes the wind turbines start rotating (cut-in wind speed) to a wind speed that makes the wind turbines stop rotating (cut-out wind speed). Between a certain wind speed and the cut-out wind speed, wind turbines operate at the rated output by controlling the blade pitch (Fig.1-1). In general, the cut-in wind speed is 3 to 4m/s, the rated wind speed is 12 to 16m/s and the cut-out speed is 24 to 25m/s [2]. This study assumes 3m/s as the cut-in speed and 24m/s as the cut-out speed. The rated speed is calculated to be 11m/s by the equation below. Power output per swept area (Pe : W/m^2) is expressed by the equation below :

$$Pe = \eta \frac{1}{2} \rho V^3$$

where V is the wind speed (m/s), ρ is the air density (1.225kg/m^3), and η is the power generation efficiency, assumed to be 40%.

Fig. 1-1 Wind Turbine Operation Pattern



1-3 Wind Conditions at Selected Sites

Fig. 1-2 shows histograms of wind speed in 2012 at the selected five sites. Fig. 1-3 shows histograms of power generation output at the five sites in 2012. The average power generation per swept area (W/m^2) ranges from 38 to 56W/m^2 at sites 2 to 5 and is 17W/m^2 at site 1. Though the rated output capacity is 354 W/m^2, rated operation is scarce. Fig. 1-4 shows histograms of power generation output hourly variation. The standard deviation at site 2 and site 4 is about 50W/m^2/h, 40W/m^2/h at site 3 and site 5, and 27W/m^2/h at site 1, which is the smallest. According to the power output by wind direction shown in Fig. 1-5, prevailing wind is observed at each of the sites. However, the wind direction is not taken into consideration for estimating power generation, as the wind turbine system can change the direction of the nacelle according to the wind direction.

Fig. 1-2 Histograms of Wind Speed at Five Sites (2012)

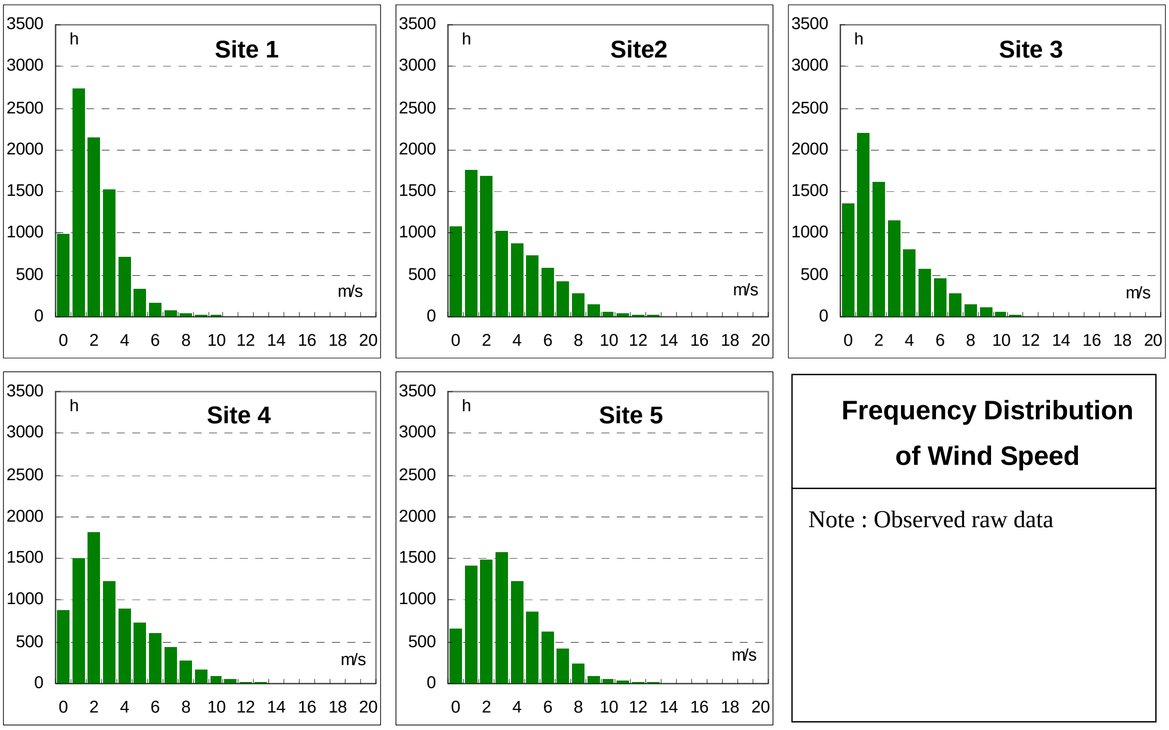


Fig. 1-3 Histograms of Power Generation Output at Five Sites (2012)

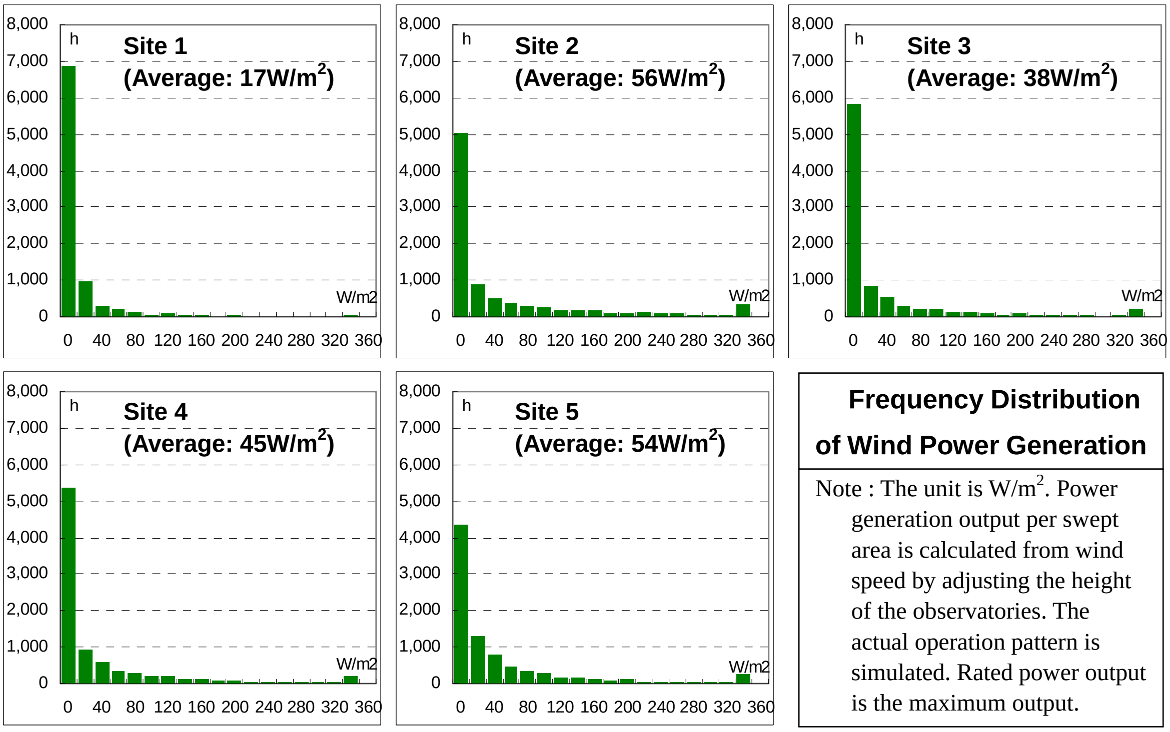
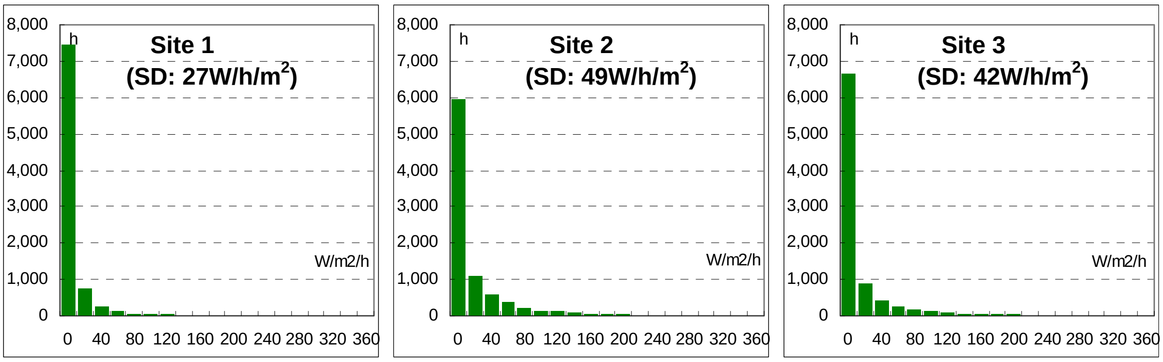
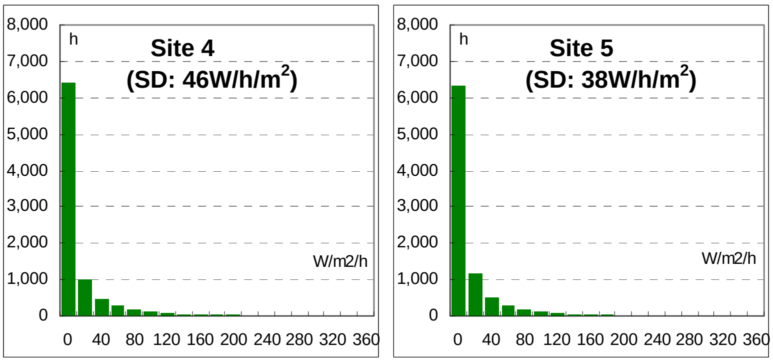


Fig. 1-4 Histograms of Power Generation Output Hourly Variation at Five Sites (2012)

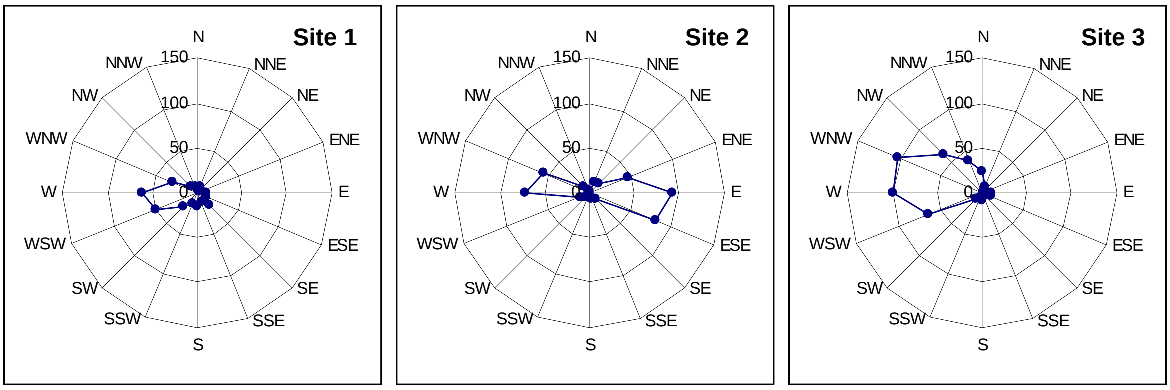


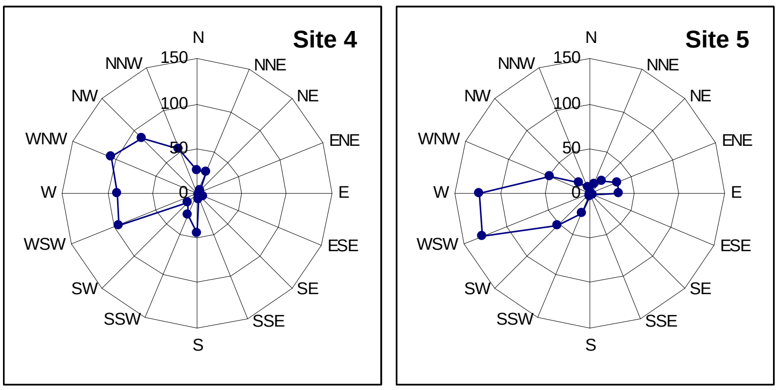


Frequency Distribution of Wind Power Generation Output Hourly Variation

Note : The unit is W/m^2/h.
The absolute value of power output hourly variation.

Fig. 1-5 Average Power Output by Wind Direction at Five Sites (2012)





Average Power Generation by Direction

Note : The unit is W/m^2. Power generation output per swept area is calculated from wind speed by adjusting the height of the observatories. The actual operation pattern is simulated.

2. Evaluation of Smoothing Effect

2-1 Optimum Locational Allocation of Wind Turbines Output Capacity

One of the ways to obtain the smoothing effect is to allocate wind turbine capacity equally among the sites. In general, individual construction sites are selected based on a survey of wind conditions. However, evaluation of how allocation of wind turbines can minimize the hourly variation of the regional total power output would give implications for promoting the construction of wind turbines. Optimization of locational allocation of wind turbines capacity is formulated as follows :

$$\text{Minimize} : \sigma(\dot{\boldsymbol{s}})$$

$$\text{Subject to} : \sum s_t = S^*$$

$$: 0 \le a_i \quad (I : 1\ldots5, \quad t : 1\ldots8760)$$

where

$\sigma(\dot{\boldsymbol{s}})$: standard deviation of $\dot{\boldsymbol{s}}$

$\dot{\boldsymbol{s}} = (s_t - s_{t-1})$: regional total power generation hourly variation at time t (W/m^2/h)

$\boldsymbol{s} = (s_t)$: regional total power generation at time t (W/m^2)

$\boldsymbol{Pa} = \boldsymbol{s}$

$\dot{\boldsymbol{P}}\boldsymbol{a} = \dot{\boldsymbol{s}}$

$\boldsymbol{P} = (P_{t\,i})$: power generation at time t at site i (W/m^2)

$\dot{\boldsymbol{P}} = (P_{t\,i} - P_{t-1\,i})$: power generation hourly variation at time t at site i (W/m^2/h)

$\boldsymbol{a} = (a_i)$: total swept area of wind turbines constructed at site i

S^* is region-total annual electricity generation (kWh/m^2) and is assumed to be the average annual electricity generation of the five sites, which means the total swept area is equally divided into five ($a_1 = a_2 = a_3 = a_4 = a_5$).

Table 2-1 shows optimization results for years from 2009 to 2012. The results do not largely vary, though wind conditions do. In 2012, the standard variation of power generation hourly variation ranges from 27 to 49W/m^2/h and annual power generation from 151 to 489kWh/m^2. The wind conditions at the five sites differ substantially. The optimized standard deviation is reduced to 19 W/m^2/h, which is smaller than the smallest standard deviation at site 1. However, optimization yields a very small improvement compared to equal allocation among the five sites. Though the output capacity share of site 5 where annual power generation is large and the standard deviation is small (see Fig.1-3 and Fig. 1-4) is largest when optimized (Fig. 2-1), the share of other sites is roughly equally divided. Optimization between site 2 and site 5 brings similar results (Table 2-1). It is presumed that equal allocation already brings results closer to minimizing the standard deviation of power generation hourly variation. Further analysis using other site combinations is required for detailed evaluation.

Table 2-1 Standard Deviation of Power Generation Hourly Variation and Annual Power Generation

	Sites 1-5		Optimization for sites 1-5			Optimization for site 2 and 5		
	σ	S	σ		S	σ		S
			Opt.	Equal allc	Opt = Equal allc	After opt.	Equal allc	Opt = Equal allc
2009	29-51	176-533	19.96	20.36	397	33.83	34.48	521
2010	32-51	192-574	19.90	20.52	411	33.14	34.22	548
2011	28-53	162-550	19.89	20.62	406	33.17	34.40	539
2012	27-49	151-489	18.95	19.35	367	31.45	32.24	480

Note : σ means standard deviation of power generation hourly variation ($W/m^2/h$), S annual power generation (kWh/m^2).
"Opt" means optimization and "Equal allc" means equal allocation.

Fig. 2-1 Optimized Share of Rated Output Capacity

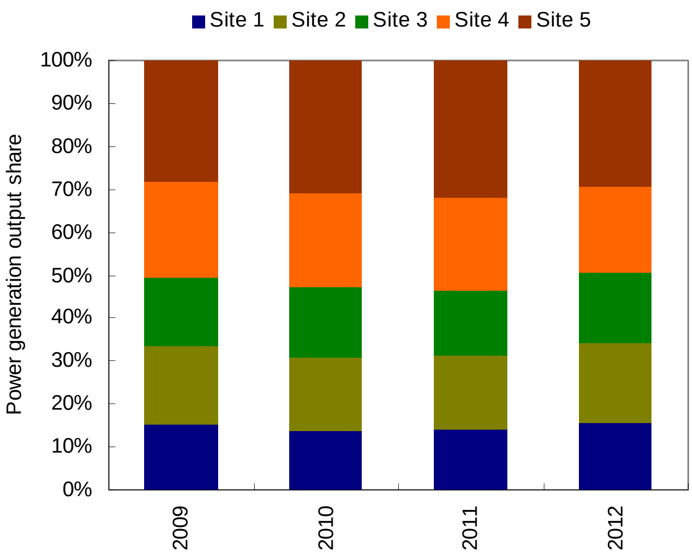
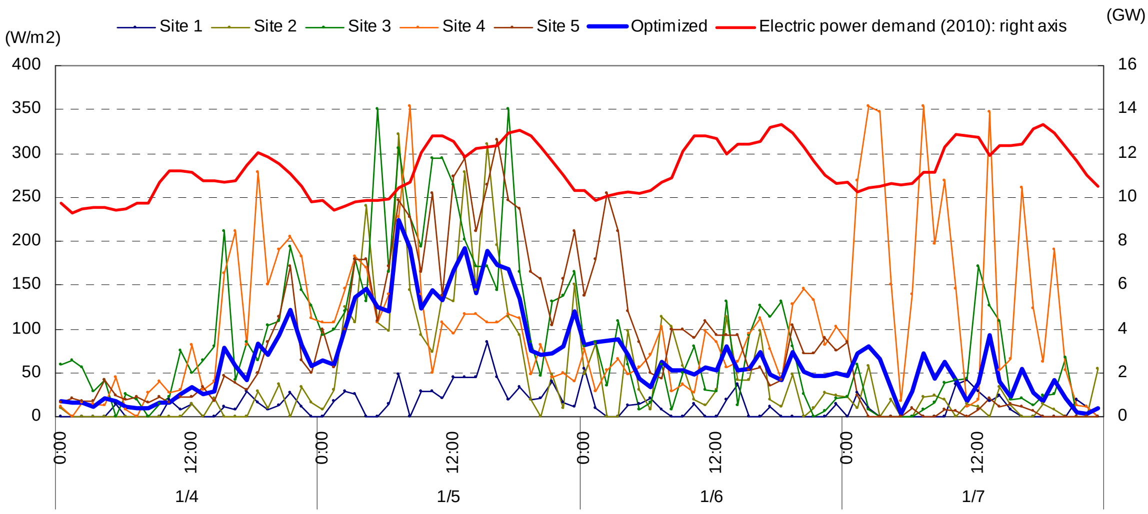


Fig. 2-2 Sample of Smoothing Effect (4 days in January 2012)



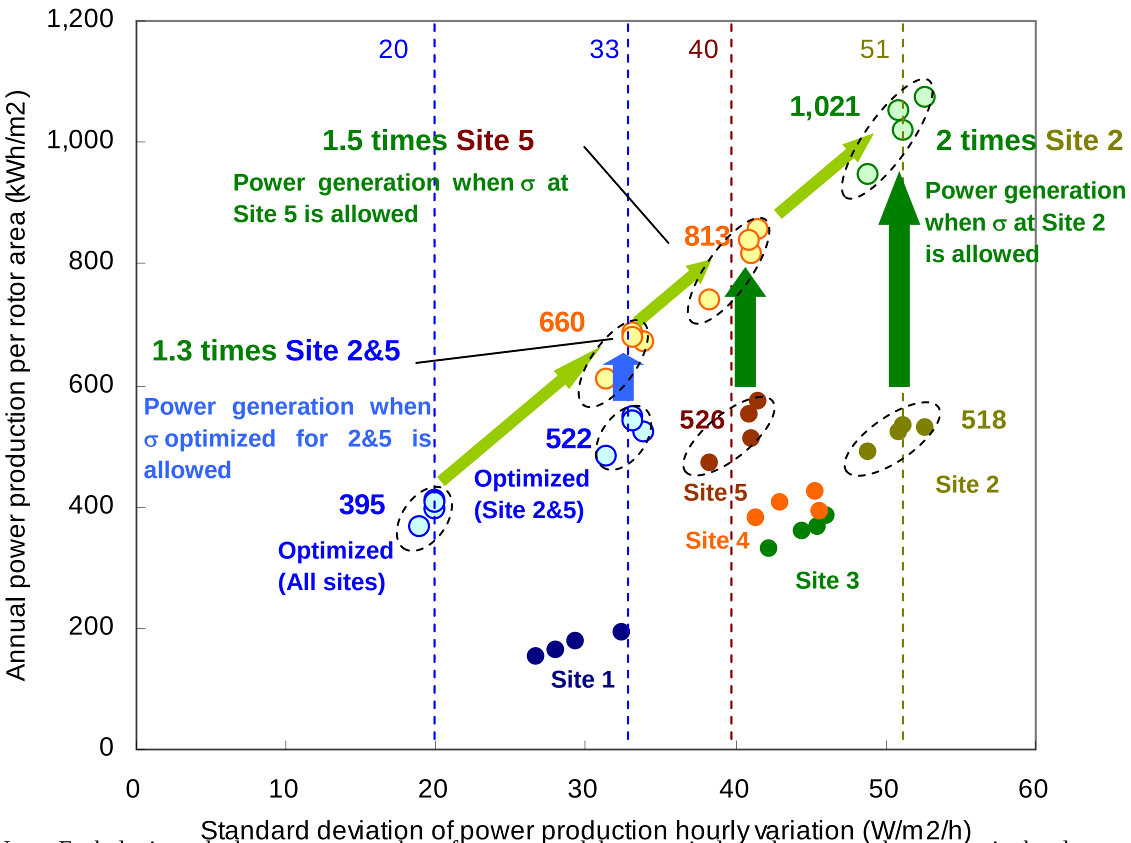
Note : Tohoku Electric Power Company is referred to for electric power demand.

Fig. 2-2 shows an example of the smoothing effect along with the electric power demand curve [3]. Wind turbine power output and electric power demand are similar in terms of uncontrollability. Optimized wind power output shows smoothed hourly fluctuation, which is nevertheless still large compared to the electric power demand (the ratio of standard deviation of hourly electric power demand variation to the average electric power demand is 0.04, while the ratio of standard deviation of hourly wind power generation variation to the average wind power generation is 0.45).

2-2 Quantification of Smoothing Effect

It is not evident what level of wind power output fluctuation the current power grid system can accept, nor what capacity of gas-fired power plant and battery are required for backup. It is therefore very difficult to evaluate the benefit brought by the smoothing effect from a technological and economical point of view. This study simply evaluates how different the maximum wind turbine capacity and annual power generation are between single-site introduction and multiple-site introduction, if a permissible value is given for the standard deviation of wind power generation output hourly variation. In other words, the maximum wind power capacity that could be introduced will be identified, keeping the impact on the power grid system constant.

Fig. 2-3 Increase in Wind Turbine Introduction Potential by Site Combination (2009-2012)



Note : Each dot in each cluster expresses data of one year and the numerical number means the average in the cluster.
Note : σ means standard deviation of power generation hourly variation ($W/m^2/h$).

Fig. 2-3 presents how wind power introduction can be increased by the smoothing effect. Generally, wind turbines are constructed at sites with good wind conditions. As the wind conditions at site 5 are most preferable followed by site 2, the annual power generation at site 5 is largest at 526kWh/m^2. However, the standard deviation of power generation hourly variation is 40W/m^2/h. In the case of site 2, the annual power generation and standard deviation are 518kWh/m^2 and 51W/m^2/h, respectively. On the other hand, optimizing among five sites improves the standard deviation to 20W/m^2/h, while reducing annual power generation to 395 kWh/m^2.

If an assumption is made that the standard deviation at site 5 is allowed by the current power grid system, optimization yields annual power generation 1.5 times as much as that of site 5 (813 kWh/m^2). If the standard deviation at site 2 is allowed, annual power generation is estimated to be 1,021 kWh/m^2, which is equal to twice that of site 2.

If wind power is developed at site 5 and site 2 and the standard deviation after optimization for these two sites (33W/m^2/h) is allowed, optimization among five sites yields 660kWh/m^2, which corresponds to 1.3 times the combination of site 5 and site 2 (522kWh/m^2).

3. Concluding Remarks

This study evaluated the smoothing effect of wind turbines in Aomori prefecture based on the hourly wind speed data. The smoothing effect is expected by combining multiple sites and locational allocation optimization of power output capacity can maximize its effect. For the five sites in this study, the additional benefit by optimization compared to equal allocation is not large. However, wind turbine development taking into account locational allocation can be one of the measures to enhance integration of wind power plants minimizing negative impact on the power grid system, since locational allocation is not considered in the actual construction of wind turbines and region-total power generation hourly variation may not be reduced.

Assuming a maximum permissible value for the standard deviation of wind power output hourly variation as a threshold of the impact on the current power grid system, the study observed a case where the smoothing effect among five sites allows twice as many wind turbines to be introduced, compared to a single site introduction. In reality, however, wind turbines are not abundantly installed in sites with good wind conditions, nor dispersed among sites. Analyses selecting the sites where the wind turbines were installed are challenges to be addressed. In addition, although this study focused on comparative analysis of standard deviation among sites, analyses of the absolute value of power generation from wind turbines taking into account the electric power demand should also be addressed.

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〈References〉

[1] "Research on Renewable Energy Introduction Potential," Ministry of Environment, March, 2011
[2] "Wind Power Introduction Guidebook," NEDO, 2008
[3] Homepage of Tohoku Electric Power Company

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