Evaluation of Wind Power Integration Potential in Japan by Strengthening of Interregional Transmission Lines and by Power Curtailment

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Summary

In Japan, the sites with better wind conditions are concentrated in northern and southern areas remote from the huge electricity consuming regions. It has been pointed out that the poor capacity of interregional transmission lines that interconnect the power grids of the regional monopoly utilities hinders wind power from being substantially exploited. This study evaluated the wind power integration potential in Japan with assumptions that the ramping-up (ramping-down) capability in regular operation of an individual utility equals the largest hourly increment (decrement) of electric demand and that totaling each regional ramping capability yields a nationwide capability by strengthening the interregional transmission lines so that the whole of Japan can be regarded as a single system without any bottlenecks at regional boundaries. On the other hand, the potential by implementing a wind power curtailment measure was also evaluated.

The wind power integration potential quadruples from 9.3-10.5GW with the current capacity of the interregional transmission lines to 32-42GW by strengthening the interregional transmission lines. However, the annual power generation from the potential wind power is no more than 60-80TWh, accounting for 6-8% of the annual electricity demand. If the interregional transmission lines are strengthened within eastern Japan and western Japan separately, taking into account the existing constraint at frequency conversion stations, the wind power integration potential was estimated to be 23-24GW and the annual power generation decreases to 43TWh.

Meanwhile, the wind power integration potential via a curtailment measure with the current capacity of interregional transmission lines was estimated to be 16-19GW and the annual power generation is 27-35TWh. Although the potential is smaller than the potential via strengthening the interregional transmission lines, the very small fractional curtailment can yield a large increase in integration potential. As strengthening of interregional transmission lines requires huge investment costs and long lead times, it is important that the curtailment measures also be strongly promoted.

This study excluded an analysis on how much capacity of interregional transmission lines will be required. Estimation of the required capacity increase to enable integration of wind power potential and analysis on the cost effectiveness compared with other measures such as energy storage and demand response taking into account photovoltaic integration would be future issues to be addressed.

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Introduction

In Japan, the sites with better wind conditions are concentrated in northern and southern areas that are remote from the huge electricity consuming regions such as the Tokyo metropolitan and Kansai metropolitan areas. It is pointed out that the poor capacity of interregional power transmission lines that interconnect the power grids of the domestic utilities hinders wind power from being substantially exploited. An analysis on additional wind power integration into the power grid by building up intraregional transmission lines [1] and an estimation of required additional interregional power transmission line capacity in certain regions on the presumption of the expected wind power capacity to be installed in the short term [2] have been carried out. However, how much wind power can be integrated into the power grid by strengthening the interregional power transmission lines nationwide has not yet been tackled.

This study evaluates the wind power integration potential in each utility jurisdiction (region) with the current interregional transmission line capacity and also analyzes nationwide wind power integration by fully strengthening the interregional transmission lines. It is presumed that strengthening interregional transmission lines will allow utilities to leverage the ramping capability of dispatchable power plants on a nationwide scale and enable more wind power to be integrated. Meanwhile, wind power curtailment is presumably a realistic measure towards larger integration of wind power, as strengthening interregional transmission lines will require huge costs and long lead times. Wind power integration via wind curtailment is also estimated and compared with wind power integration via strengthening the interregional transmission lines.

The analyses are carried out using the data of the hourly electric demand of the nine utilities and the hourly wind power generation estimated from wind speed data for the past three years.

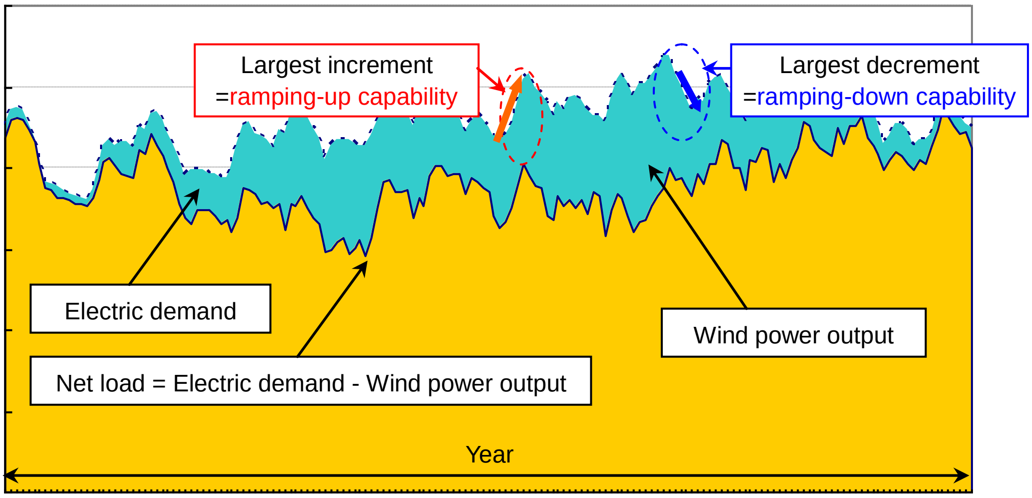
1. Methodology

1-1 Interpretation of Ramping Capability of Electric Utility

The maximum ramping capability varies by dispatchable power plant. For example, the IEA's "Harnessing Variable Renewables" [3] states that coal-fired plants can respond to 50% of their rated capacity within 1 hour, open cycle gas turbines 100% and nuclear 33%. Besides, ramp rates differ between ramping-up and ramping-down. These ramping capabilities are not much more than the potential and they are not always ready for maximizing to their greatest extents. In addition, power plant maintenance and troubles prevent us from accurately ascertaining how much ramping capabilities are available in which power plant in which period. On the other hand, electric utilities maintain stable power supply at all times by having their aggregated power plants follow the variable electric demand by controlling the power output of each of their power plants. Assuming this operation of electric utilities as "business as usual," the ramping capability of the aggregated power plants can be identified from the hourly electric demand (load curve) of electric utilities, even if the operation pattern of the individual power plants is unknown (Fig. 1-1). In other words, electric utilities at least possess the ramping-up capability equivalent to the largest hourly increment of the electric power demand and the ramping-down capability equivalent to the largest hourly decrement. These ramping capabilities can be interpreted as the capacity that electric utilities are able to demonstrate without excessive effort, subject to the hourly electric demand variation.

The wind power is able to be integrated to the extent that the largest hourly increment (decrement) of the remaining electric demand after subtraction of wind power output (net load[1]) does not exceed the ramping-up (ramping-down) capability (Fig. 1-1).

Fig. 1-1 Identification of Ramping Capability of the Aggregated Dispatchable Power Plants and Net Load



1-2 Interpretation of Impact of Strengthening Interregional Transmission Lines

Wind power integration differs with the ramping capability of the electric utility and the status of interregional transmission lines as shown Table 1-1. The impact brought by the current interregional transmission line capacity is embedded in the ramping capabilities of each region identified from the hourly electric demand. Strengthening interregional transmission lines in this study means that the bottlenecks at interregional boundaries are fully removed and the nationwide power grid is assumed to be a single system. Hence, the sum of the ramping capabilities of each region identified in 1.1 can be regarded as the nationwide ramping capability. Overestimate of the total ramping capability caused by summation of the ramping capability of each region that embeds the contribution from the current interregional transmission line capacity should be avoided. However, since information on the period when electric power interchanges occur is not available, what percentage of the ramping capability the electric power interchange effect accounts for cannot be determined. Therefore, the ratio of the annual electric power interchange in the annual electricity demand is taken away from the ramping capability.

This study, in other words, analyzes how much wind power integration can be increased from

[1] Net load is the electricity demand that is met by dispatchable power plants, not by variable renewables such as photovoltaic and wind.

case 2, the sum of the wind integration of each region, to case 5, nationwide wind integration, in Table 1-1. For the sake of simplicity in discussion, intraregional transmission lines are assumed to be sufficiently established.

It should be noted that the estimated wind power integration potential could be underestimated in terms of a "business-as-usual" operation assumption, while overestimated in terms of neglecting the geographical distance between the dispatchable power plants and the net load.

Table 1-1 Combination of Measures in Grid System for Variable Renewables Integration

Case	Ramping capability	Interregional transmission line
1	Regular operation ~ critical operation	None (each region is a closed system)
2	Regular operation	Current situation
3	Critical operation	Current situation
4	Regular operation ~ critical operation	Partial strengthening
5	Regular operation	Full strengthening (whole country as a single system)
6	Critical operation	Full strengthening (whole country as a single system)

Note : Battery and demand side measures are outside the scope of this study.
Note : Critical operation means that each power plant uses its maximum ramping capability.

1-3 Assumption of Location for Wind Turbines Construction

As it is impossible to identify the locations where new wind turbines would be constructed, the historical trend of cumulative installed capacity in each region [4] is assumed to continue in future years. The existing wind turbine locations are allocated to the selected AMeDAS (Automated Meteorological Data Acquisition System) observatories by each region (See 2.1). The wind power capacity is assumed to increase, keeping the proportion among observatory locations constant.

1-4 Electricity Demand

The hourly electric demand data of each electric utility is prepared for the year 2012. If only weekday data are available, the weekend and holiday data are estimated (See 2.2).

1-5 Analysis Outline

Fig. 1-3 shows the analysis flow. The hourly electric demand data of 2012 is used, while the hourly wind power generation is estimated from wind speed data for the past three years, 2010, 2011 and 2012. As the year 2012 is a leap year, the last day of 2012 is excluded in case of the analysis using the wind speed data of 2010 and 2011.

First, the "business-as-usual" ramping capability (up and down) of each region is identified from the electric load curve. Second, the hourly wind power generation curve per unit capacity in each region is estimated. Third, the wind power output capacity is identified so that the largest increment/decrement of the hourly net load coincides with the ramping-up/ramping-down capability. The smaller wind power capacity identified based on the ramping-up capability and ramping-down capability is interpreted as the additional integration potential in the individual region and the sum of the each region is the nationwide additional potential. On the other hand, summing the ramping capability of each region (excluding the impact from power interchange) and analyzing in the same way as above leads to estimation of the nationwide additional wind power integration potential by fully strengthening interregional transmission lines. In addition, the additional wind power integration potential in eastern Japan and western Japan will be separately estimated, taking into account a bottleneck at the frequency conversion facilities, as Japan is divided into eastern 50Hz and western 60Hz regions (Fig. 1-2).

Among the major conditions that cap the wind power integration are the LFC (Load Frequency Control) capacity in short period variation (up to 20 minutes) and the ramping capability in a long period (more than 20 minutes). This study deals with ramping capability per hour, due to the availability of data granularity. There is also a constraint of lack of dispatchable capacity that the total of wind power output and base load power plant output should not exceed the electric demand. This constraint is neglected as being greatly dependent on the power generation mix at the bottom demand period and also the current and future power generation mix is totally uncertain. Nevertheless, the net load is calculated and checked. This study also excluded a network analysis taking into account intraregional transmission lines and the geographic distance between wind turbines and transmission lines required for the in-depth analysis, due to data availability constraints and for the sake of simplicity.

On the other hand, the wind power integration potential via wind power curtailment is also analyzed with an assumption of the current interregional transmission capacity. Wind power output capacity that maximizes the annual power generation is identified, curtailing the wind power generation that causes the events where the maximum increment of net load exceeds the ramp-down capability. As the wind curtailment can possibly lead to an estimation of huge integration potential that neglects the bottom net load, the analysis is carried out subject to the reduction ratio of the minimum nationwide net load estimated in the case where the wind power integration potential via strengthening interregional transmission lines is introduced (See 3.3).

Fig. 1-2 Electric Utilities and Regional Frequency Gap in Japan

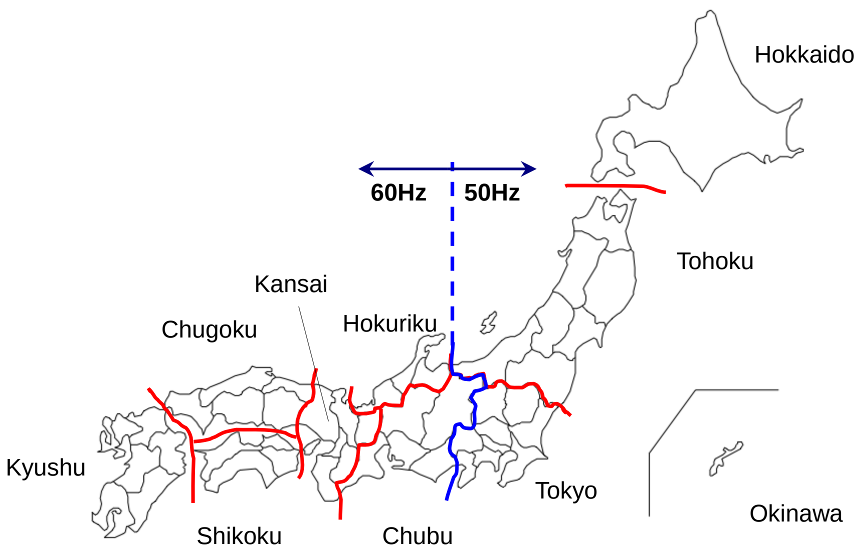
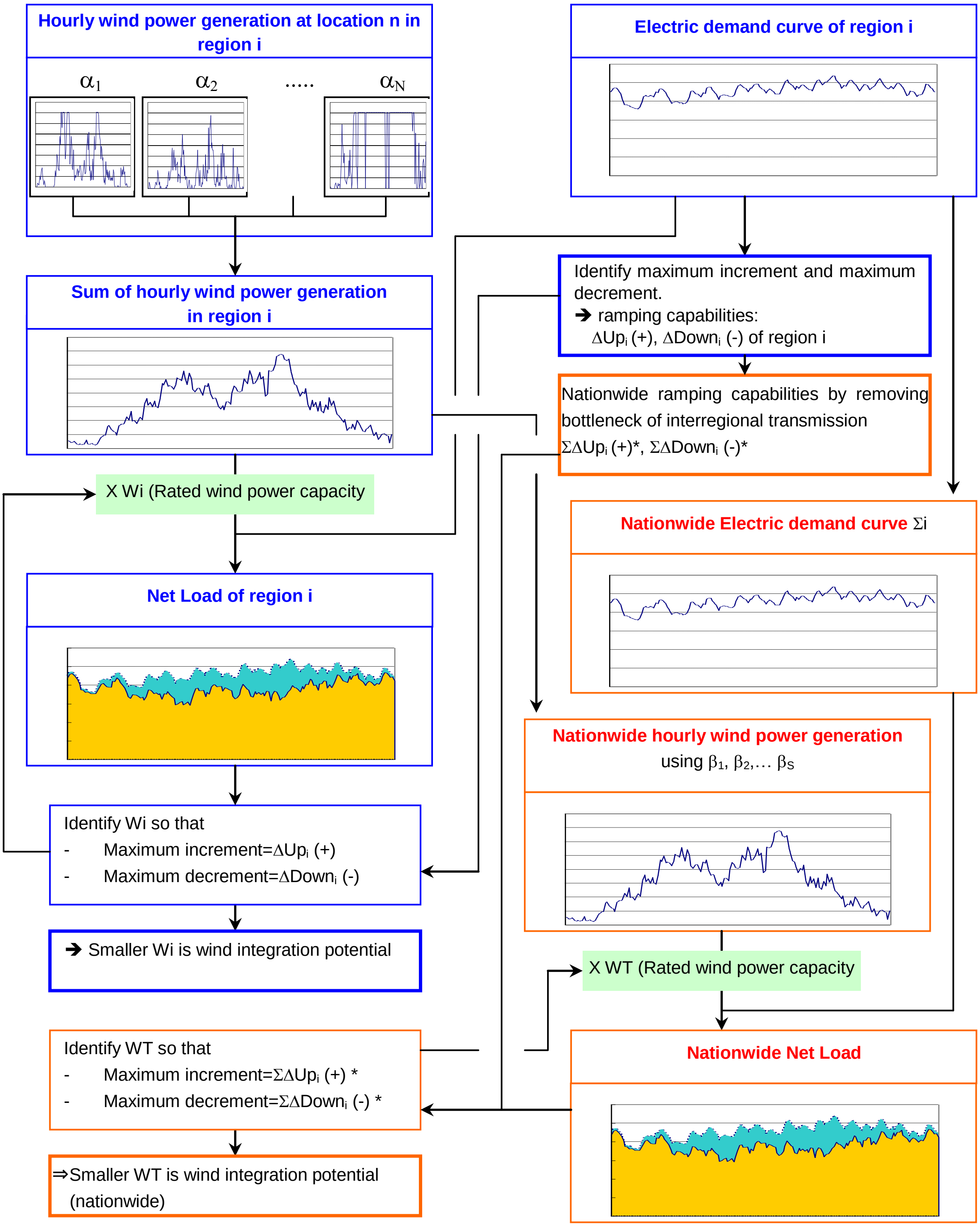


Fig. 1-3 Flow for Analysis of Wind Power Integration Potential by Strengthening Interregional Transmission Lines



Note : α_n is the ratio of wind turbine capacity at each location in each region. β_n is the ratio of wind turbine capacity at each region. ΔUp_i (+) and $\Delta Down_i$ (-) are ramping-up capability and ramping-down capability, respectively in the region i and the unit is kW/h. The hourly electric demand data in 2012 and the hourly wind power generation data in 2010, 2011 and 2012 are used, which means analyses are made for three cases. The wind power integration potential estimated here is the additional capacity to the existing capacity.

* The contribution from power interchange is subtracted.

2. Preparation of Data

2-1 Hourly Wind Power Generation Output

The hourly wind power generation is calculated from the wind speed data of AMeDAS. By comparing the locations (municipalities) of individual wind turbines existing as of March 2012 collected in the list prepared by NEDO [4] and the AMeDAS observatory locations, the wind turbine locations are aggregated into selected neighboring observatories. Table 2-1 shows the selected observatories and capacity of the wind turbines aggregated into each observatory. 2,560MW of wind turbine capacity was allocated to 89 observatories. Excluding remote islands unconnected to major transmission lines and Okinawa that needs undersea transmission lines to be connected with Kyushu decreases this to 2,530MW in 82 locations.

Some locations where wind turbines used to be installed but were removed as of March 2012 are included in view of future possibility of reconstruction.

Table 2-1 Selected Observatory Locations

Region	Observatory	Capacity(kW)
Hokkaido (10)	Ishikari	5,844
	Esashi	55,500
	Erimomisaki	1,200
	Nemuro	15,100
	Hakodate	3,700
	Hahoro	88,770
	Muroran	14,450
	Wakkanai	82,765
	Okoppe	0
	Suttsu	21,080
	Total	288,409
Tohoku (15)	Kanita	19,540
	Ohma	233,903
	Fukaura	2,750
	Nobechi	50,900
	Ichiura	0
	Kamaishi	42,919
	Kuzumaki	24,180
	Akita	77,761
	Noshiro	41,100
	Kaduno	7,650
	Obanazawa	6,500
	Sakata	39,290
	Onahama	140
	Koriyama	143,720
	Takada	7,010
	Aikawa	0
	Total	697,363
Tokyo (9)	Mito	13,220
	Kajima	73,080
	Maebashi	340
	Kisaradu	5,590
	Katsuura	3,250
	Choshi	59,310
	Edogawa	3,650
	Miyakejima	500
	Yokohama	7,170
	Utsunomiya	840
	Total	166,950
Hokuriku (6)	Tomari	1,500
	Tonami	1,800
	Kanazawa	1,500
	Shiga	49,415
	Wajima	69,980
	Mikuni	21,800
	Total	145,995
Chubu (9)	Nagano	0
	Ena	9,200
	Inatori	16,800
	Irouzaki	34,800
	Omaezaki	92,510
	Irako	49,236
	Toyohashi	5,010
	Ueno	33,000
	Tsu	36,047
	Total	276,602
Kansai (6)	Otsu	1,500
	Miyadu	4,500
	Ikuno	220
	Nandan	43,100
	Gojyo	60
	Wakayama	75,280
	Total	124,660
Chugoku (9)	Kurayoshi	36,600
	Matsue	102,870
	Saigo	1,800
	Hamada	46,150
	Chiya	17
	Kure	0
	Yuya	7,950
	Shimonoseki	95,000
	Yanai	10,500
	Total	300,887
Shikoku (6)	Tokushima	19,500
	Seto	67,700
	Murotomisaki	300
	Kochi	2,950
	Yusuhara	21,200
	Sukumo	12,000
	Total	123,650
Kyushu (12)	Fukuoka	17,416
	Saga	42,695
	Shimabara	4,600
	Fukue	32,400
	Hirado	69,970
	Waniura	1,200
	Ushibuka	600
	Kumamoto	30,160
	Kusu	11,490
	Nobeoka	750
	Akune	56,530
	Kagoshima	88,500
	Makurazaki	48,925
	Tanegashima	670
	Naze	2,590
	Okinoerabu	1,200
	Total	409,696
Okinawa		21,080
Nationwide(89)		2,555,291
excluding remote islands(82)		2,528,051

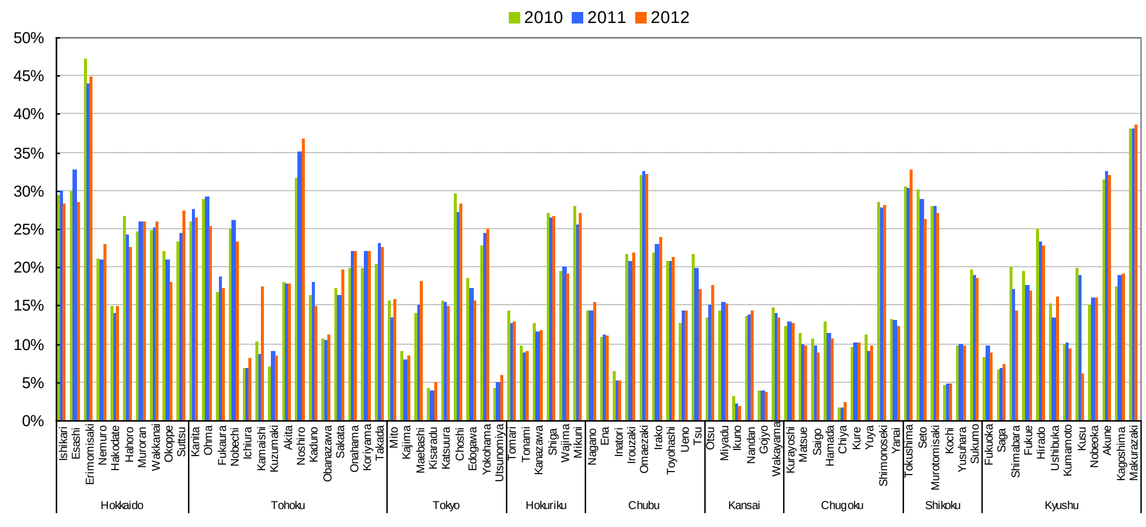
Note : Remote islands and Okinawa shown in color are excluded from the analysis. The figures in parentheses are the numbers of selected observatory locations excluding remote islands and Okinawa. Only observatory locations with wind speed recorded are selected.

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. Base on this operation pattern, hourly wind power generation is calculated from the wind speed [5]. 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. The coefficient that describes the features of the land surface that is required to convert wind speed at the height of the observatories into wind speed at the height of the wind turbine is identified by scrutinizing the features of the land surface (prairie, coast, pastoral, urban area, etc.) in an atlas.

Fig. 2-1 shows the calculated capacity factor of wind turbines at the selected locations. The capacity factor widely ranges from over 40% at Erimomisaki in Hokkaido and Makurazaki in Kagoshima to a few percent at Kisaradu in Chiba, Gojyo in Nara, and Chiya in Okayama, though it does not largely vary by year.

In terms of regional basis (Table 2-2), the capacity factor in Hokkaido, Tohoku, Hokuriku, Chubu, Shikoku and Kyushu exceeds 20%, while it falls below 20% in Tokyo, Kansai and Chugoku. The cumulative installed capacity correlates with the capacity factor. The nationwide capacity factor indicates values from 21% to 22% for the past three years, which is close to the generally recognized 20%.

Fig. 2-1 Capacity Factor at Selected Locations



Note : Remote islands and Okinawa are excluded.

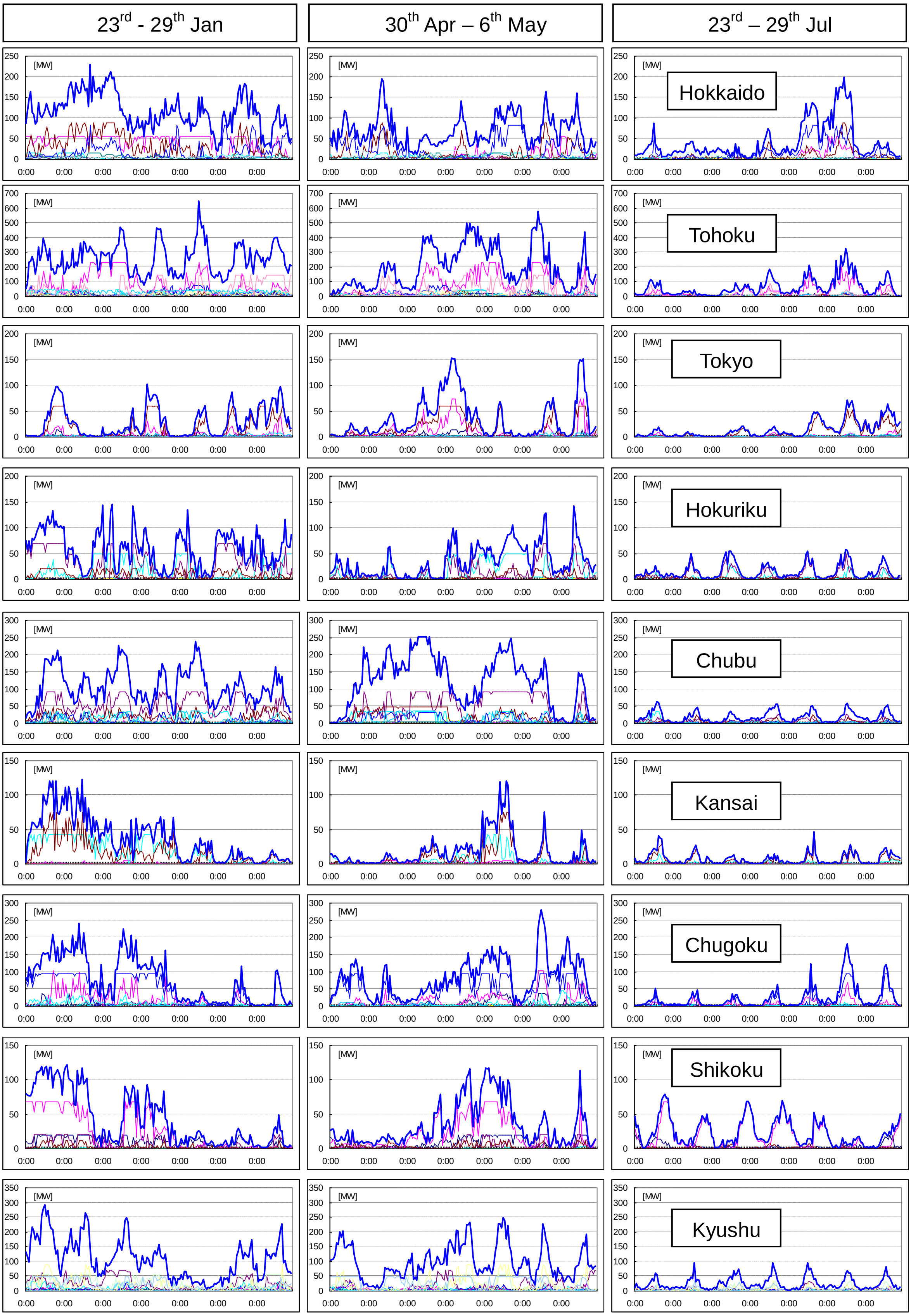
Table 2-2 Capacity Factor and Cumulative Installed Capacity of Wind Turbines by Region

	Capacity factor			Cumulative installed capacity (MW)
	2010	2011	2012	
Hokkaido	26%	26%	25%	288
Tohoku	23%	23%	23%	697
Tokyo	18%	16%	17%	166
Hokuriku	23%	23%	23%	146
Chubu	23%	23%	23%	277
Kansai	14%	14%	14%	125
Chugoku	17%	16%	16%	301
Shikoku	25%	24%	23%	124
Kyushu	21%	21%	21%	404
Nationwide	22%	22%	21%	2,528

Note : Remote islands and Okinawa are excluded.
Note : Cumulative installed capacity is as of March 2012.

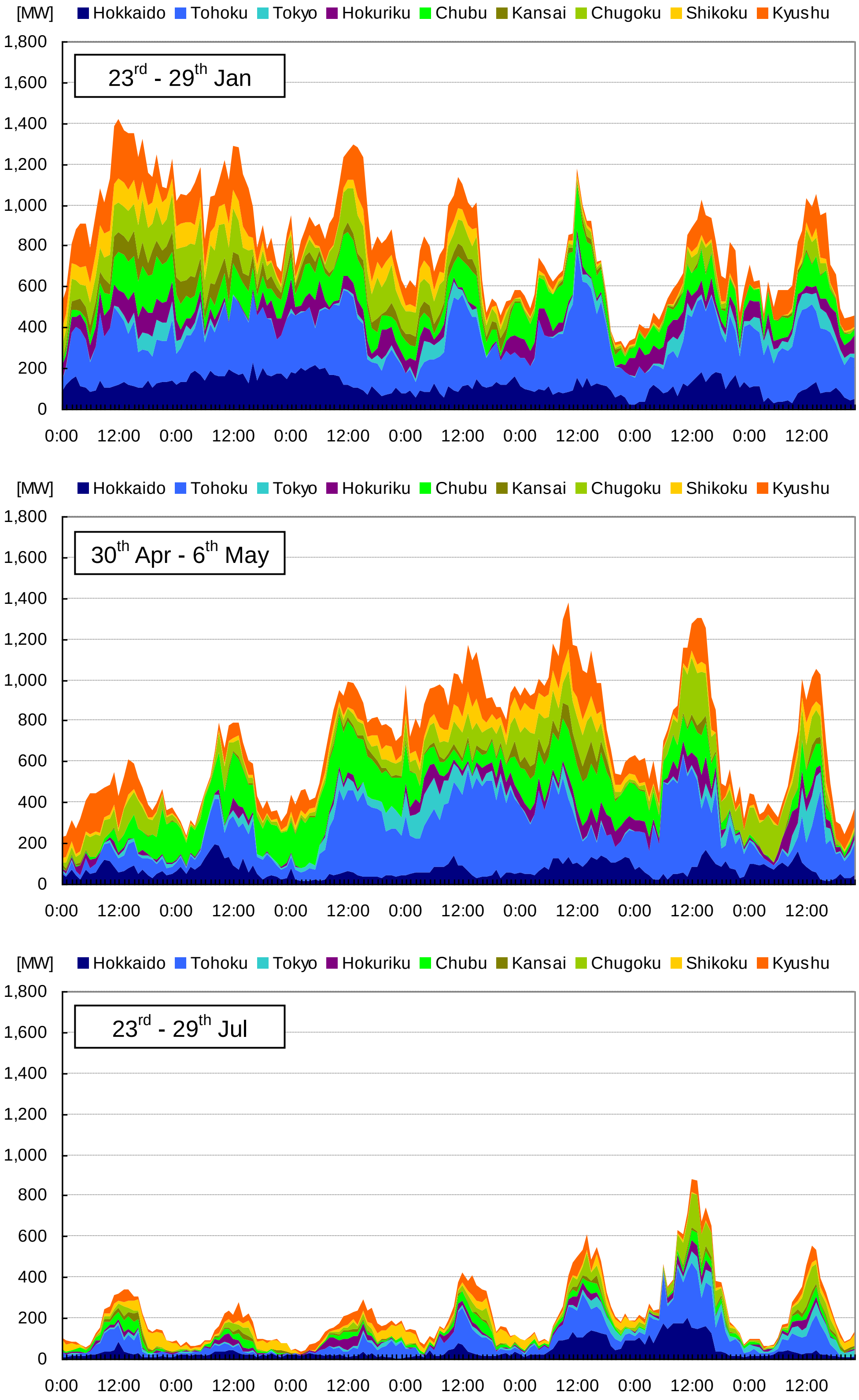
Fig. 2-2 shows typical weekly hourly wind power generation curves of the existing 2,530MW for three seasons in 2012. Wind power generation is largest in winter and also larger in the electric demand bottom seasons (April to May) in all regions. Meanwhile, power generation in summer is considerably small. Hours that show power generation with more than 50% of rated output (See Table 2-2) are frequently observed in winter and the bottom season, though few hours are observed in summer. Fig. 2-3 presents the nationwide summed wind power generation curve. The nationwide capacity factor is 28% in winter (January to March and November to December), 20% in the bottom season (April to May and October) and 13% in summer (June to September).

Fig. 2-2 Weekly Wind Power Generation Curve by Region for Three Seasons in 2012



Note : Thin lines represent locations in each region, and thick lines represent sums of the locations. The total cumulative installed wind turbine capacity as of March 2012 is 2,530MW.

Fig. 2-3 Nationwide Weekly Wind Power Generation Curve for Three Seasons in 2012



Note : The total cumulative installed wind turbine capacity as of March 2012 is 2,530MW.

2-2 Hourly Electric Demand

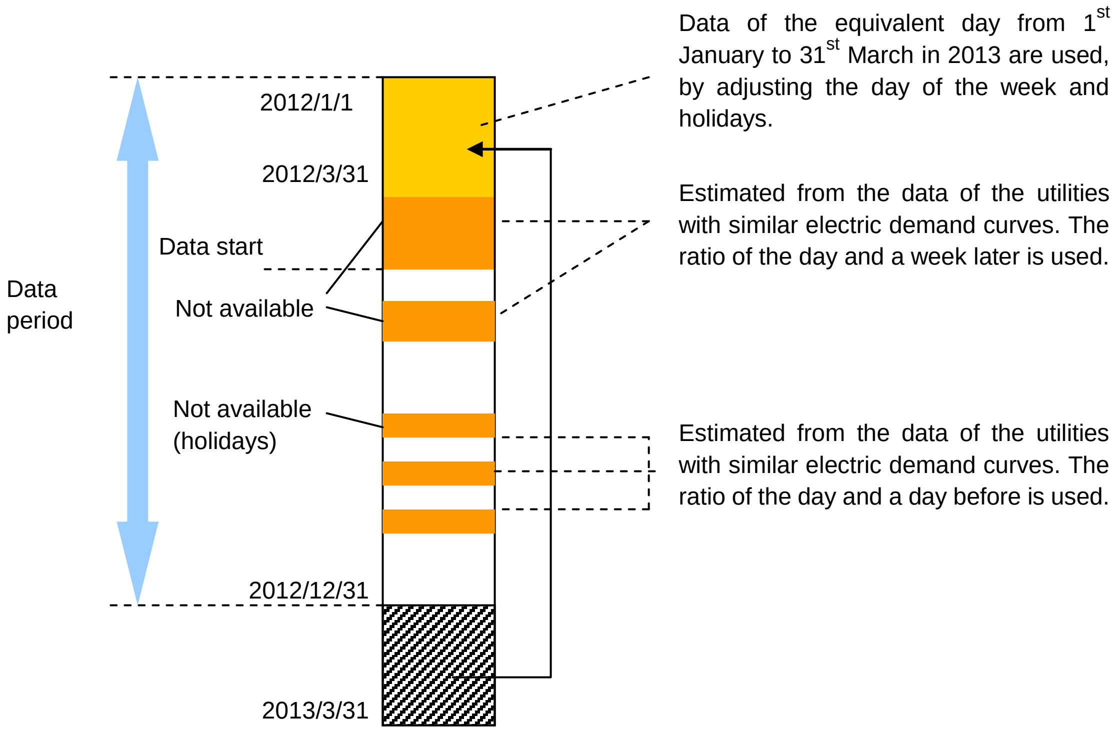
Though the hourly electric demand data can be collected from utilities websites, differences in data availability among the utilities limit the common period when the data of all utilities (excluding Okinawa Electric Power Company that is on the remote island) are available. Since few utilities provide data before 2012, the period from 1st January 2012 to 31st December 2012 (8,784 hours, as 2012 is a leap year) is taken for the data period.

In the utilities that provide data from a date after 1st January 2012, the data of the equivalent dates in 2013 are used for 1st January to 31st March 2012 by adjusting the day of the week and holidays. The data from 1st April 2012 are estimated using the ratio of electric demand of the hour of the day to that of a week later (same hour and same day of the week) in the utilities with similar electric demand curves.

Unavailable holiday data are estimated using the ratio of electric demand of the hour of the day to that of a day before (same hour) in the utilities with similar electric demand curves.

The method to estimate hourly electric demand based on the same day of the week and from similar electric demand patterns was applied from the methodologies to estimate baselines[2] used for demand response and energy saving measures [6][7][8].

Fig. 2-4 Logic of Estimation for Unavailable Hourly Electric Demand Data



Note : Hokuriku and Chugoku do not provide data of holidays. Shikoku and Kyushu do not provide data of the first half of 2012. The whole annual hourly data of the other utilities are available.

[2] Baseline is the estimate of energy that would otherwise have been consumed if demand response or energy saving measures were not taken. The baseline is necessary to identify the impacts from these measures.

Fig. 2-5 Weekly Electric Demand Curve for Three Seasons in 2012

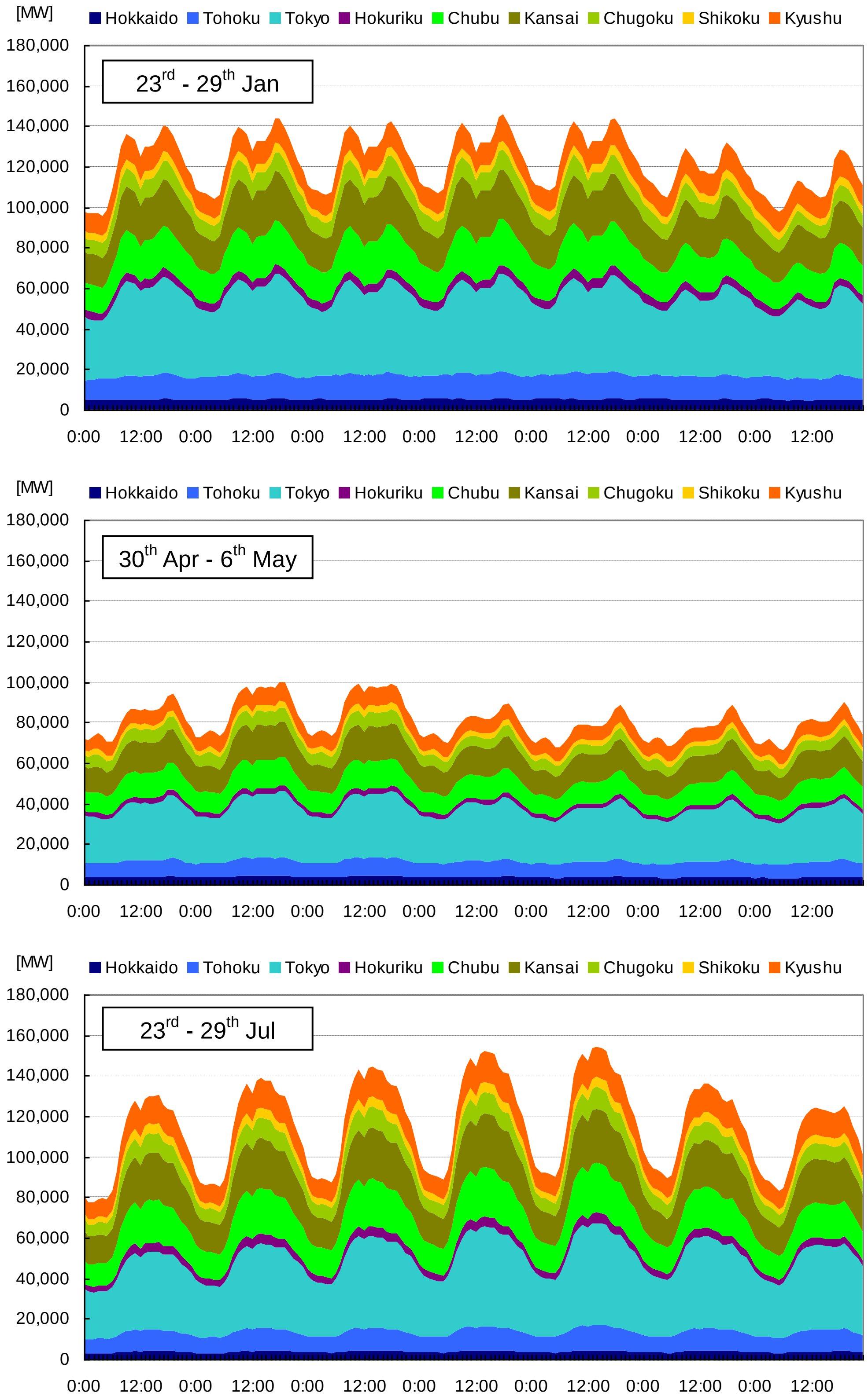


Fig. 2-5 shows samples for weekly electric demand curve estimated. The utilities other than Hokkaido and Tohoku that record their bottom electric demand in the middle of August record their bottom from late April to early May. The peak demand is recorded in February in Hokkaido and Tohoku, and in July to August in the other regions. Table 2-3 shows peak demand and bottom demand in 2012 in each region.

Table 2-3 Peak Demand and Bottom Demand in 2012

	Peak Demand (GW)	Bottom Demand (GW)
Hokkaido	5.7	2.7
Tohoku	13.6	6.5
Tokyo	50.8	20.5
Hokuriku	5.3	2.0
Chubu	24.8	8.8
Kansai	26.8	11.0
Chugoku	10.9	4.4
Shikoku	5.3	2.0
Kyushu	15.2	5.8
Whole of Japan	154.5	66.0

Note : The peak demand and bottom demand of the whole of Japan come from the summed electric demand curve and the sum of peak/bottom demand does not coincide with the peak/bottom demand of the summed electric demand.

3. Wind Power Integration Potential

3-1 Identifying Ramping Capabilities of Electric Utilities

Table 3-1 shows the estimated ramping capabilities of each utility, by regarding the largest hourly increment of electric demand as the ramping-up capability and the largest hourly decrement of electric demand as ramping-down capability. As discussed in Section 1, these ramping capabilities are interpreted as the capacity that the electric utilities can demonstrate without excessive effort, subject to the hourly electric demand variation.

The ratio of the ramping-up capability to the peak demand ranges from 10% to 20%, and that of the ramping-down capability lies in around 10%. Tokyo, Chubu and Kansai with large electricity demand possess large ramping capability, 4GW/h to 8GW/h of ramping-up and 2GW/h to 4GW/h of ramping-down. Tohoku, Chugoku and Kyushu follow with 1GW/h to 2GW/h ramping-up and ramping-down capability, while Hokkaido, Hokuriku and Shikoku have capability less than 1GW/h. It is observed that the absolute value of the ramping-down capability is smaller than the ramping-up capability in most of the utilities.

Summing up the ramping capabilities of each utility and subtracting the contribution from electric power interchanges through current interregional transmission (=9.2% ; See note of Table 3-1) yields the nationwide ramping capability to be realized from totally removing the bottleneck by strengthening interregional transmission lines. The ramping-up capability is estimated to be 21.7GW/h and the ramping-down capability 12.5GW/h. If the interregional transmission lines are strengthened separately in eastern and western Japan, the ramping capabilities of western Japan would be greater than those of eastern Japan.

Table 3-1 Ramping Capability of Each Utility

	Ramping capability		Ratio to peak demand	
	Ramping-up (GW/h)	Ramping-down (GW/h)	Ramping-up capability	Ramping-down capability
Hokkaido	0.6	-0.4	11%	-7%
Tohoku	2.1	-1.0	15%	-8%
Tokyo	8.2	-4.5	16%	-9%
Hokuriku	0.8	-0.4	15%	-8%
Chubu	4.6	-2.2	18%	-9%
Kansai	3.6	-2.0	13%	-7%
Chugoku	1.6	-0.9	15%	-8%
Shikoku	0.8	-0.4	15%	-7%
Kyushu	1.6	-1.9	10%	-13%
Whole of Japan*	21.7	-12.4	14%	-8%
Eastern Japan*	9.9	-5.3	14%	-8%
Western Japan*	11.8	-7.1	13%	-8%

Note : The hourly electric demand data prior to 2012 that Hokkaido, Tohoku, Tokyo and Chubu provide on their websites are included in identifying the ramping capabilities, though the data after the East Japan Great Earthquake (11th March 2011) are excluded. The largest increment (=ramping-up capability) and the largest decrement (=ramping-down capability) of Tokyo were observed in 2010, the largest increment of Chubu in 2010, the largest increment and largest decrement of Tohoku in 2010, and the largest increment and largest decrement of Hokkaido in 2011. The other increments/ decrements were observed in 2012. The ratio of ramping-down capability to peak demand of Kyushu, larger than other utilities, is presumably caused by electric demand estimation.

* Reduced by 9.2% from the summation. 9.2% is the ratio of the annual electricity interchange to the annual electricity demand, estimated from "Electric Power Interchange, 2012" of Electric Power System Council of Japan.

3-2 Estimation of Wind Power Integration Potential by Strengthening Interregional Transmission Lines

(1) Nationwide

Table 3-2 presents the additional wind power integration potential that is estimated subject to the ramping capabilities based on the hourly electric demand in 2012 and hourly wind power generation in 2010, 2011 and 2012. Though the wind condition determines which will be the dominant constraint, ramping-up capability or ramping-down capability, many regions show that ramping-down capability imposes a constraint over ramping-up capability. The smaller wind integration between subject to ramping-up capability and subject to ramping-down capability specifies the wind integration potential. The sum of wind power integration of the individual utilities ranges from 6.8GW (wind condition of 2012) to 8.0GW (that of 2010). This means that the current interregional transmission capacity allows 6.8GW to 8.0GW of additional nationwide wind power integration without significantly affecting the operation of dispatchable power plants. The estimated additional wind power integration potential of most of the utilities is smaller than the acceptable wind power minus the existing wind power (See Table A-1 in Appendix) reported by the Federation of Electric Power Companies of Japan. This difference stems from differences in methodology and assumptions.

The additional nationwide wind power integration potential is increased to 30GW (wind condition of 2012) to 38GW (that of 2010) by fully strengthening the interregional transmission lines so as to regard the whole country as a single grid system without bottleneck.

Table 3-2　Additional Wind Power Integration Potential by Strengthening Interregional Transmission Lines

Year of wind data	Region /Utility	Integration Potential (GW)			Net load when potential is integrated		Standard deviation of hourly variation of net load (GW/h)		Wind power integration by strengthening interregional transmission (GW)[2]
		Subject to ramping(+)	Subject to ramping(-)	The smaller	Peak demand (GW)	Bottom demand (GW)	Before integration	After integration of potential	
2010	Hokkaido	0.8	0.1	0.1	5.6	2.7	0.2	0.2	4.5
	Tohoku	2.7	0.9	0.9	13.5	6.2	0.4	0.4	10.9
	Tokyo	8.8	4.4	4.4	50.4	18.6	1.6	1.7	2.6
	Hokuriku	0.3	0.1	0.1	5.2	1.9	0.2	0.2	2.3
	Chubu	7.4	1.5	1.5	24.3	8.6	0.8	0.8	4.3
	Kansai	1.1	0.4	0.4	26.8	11.0	0.9	0.9	1.9
	Chugoku	2.2	0.2	0.2	10.8	4.4	0.3	0.3	4.7
	Shikoku	0.7	0.0	0.0	5.3	2.0	0.2	0.2	1.9
	Kyushu	0.3	1.8	0.3	15.1	5.7	0.4	0.4	6.3
	Total	―	―	8.0	―	―	―	―	39.4
	Japan[1]	69.7	39.4	39.4	147.6	53.9	4.55 (4.3%)[3]	4.60 (4.4%)[3]	39.4
2011	Hokkaido	0.5	0.2	0.2	5.6	2.7	0.2	0.2	4.0
	Tohoku	5.2	0.5	0.5	13.6	6.5	0.4	0.4	9.7
	Tokyo	10.1	4.2	4.2	50.6	19.1	1.6	1.7	2.3
	Hokuriku	0.7	0.1	0.1	5.3	2.0	0.2	0.2	2.0
	Chubu	6.8	1.6	1.6	24.2	8.3	0.8	0.8	3.9
	Kansai	0.1	0.3	0.1	26.8	11.0	0.9	0.9	1.7
	Chugoku	2.5	0.7	0.7	10.7	4.0	0.3	0.3	4.2
	Shikoku	0.0	0.2	0.0	5.2	2.0	0.2	0.2	1.7
	Kyushu	0.0	1.4	0.0	15.2	5.8	0.4	0.4	5.6
	Total	―	―	7.5	―	―	―	―	35.2
	Japan[1]	85.3	35.2	35.2	148.3	58.2	4.55 (4.3%)[3]	4.56 (4.3%)[3]	35.2
2012	Hokkaido	0.5	0.1	0.1	5.6	2.7	0.2	0.2	3.4
	Tohoku	4.2	0.4	0.4	13.5	6.5	0.4	0.4	8.2
	Tokyo	7.5	4.7	4.7	49.8	17.8	1.6	1.7	2.0
	Hokuriku	0.1	0.1	0.1	5.2	1.9	0.2	0.2	1.7
	Chubu	10.5	0.1	0.1	24.8	8.8	0.8	0.8	3.2
	Kansai	1.0	1.6	1.0	26.6	10.8	0.9	0.9	1.5
	Chugoku	0.0	0.2	0.0	10.8	4.3	0.3	0.3	3.5
	Shikoku	0.5	0.2	0.2	5.2	1.9	0.2	0.2	1.5
	Kyushu	0.3	0.1	0.1	15.2	5.7	0.4	0.4	4.7
	Total	―	―	6.8	―	―	―	―	29.7
	Japan[1]	79.2	29.7	29.7	147.9	55.8	4.54 (4.3%)[3]	4.56 (4.3%)[3]	29.7

Note 1 : The nationwide wind power integration potential by strengthening interregional transmission lines.
Note 2 : Estimation based on the regional ratio of cumulative installed wind power as of March 2012.
Note 3 : The ratio to the annual average hourly electric demand.

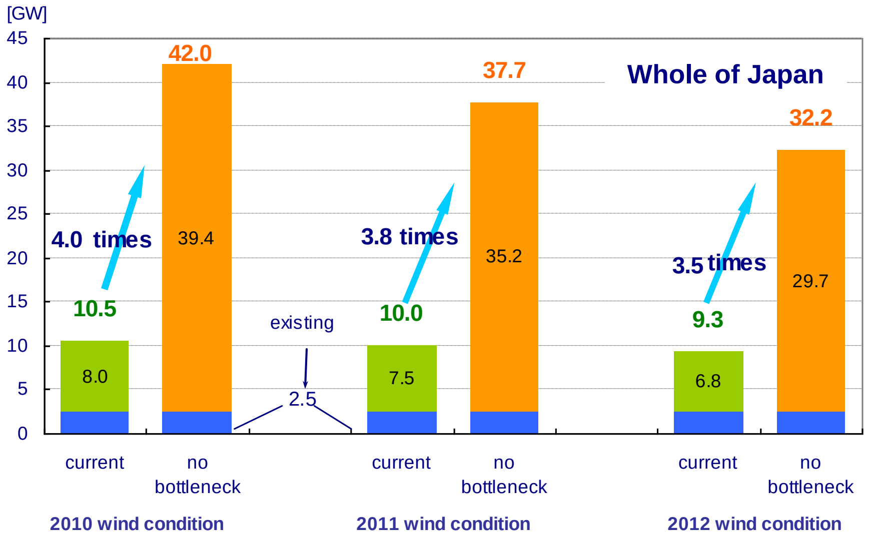
Including the existing wind turbines as of March 2012 (2.53GW, excluding Okinawa and remote islands), the integration potential with the current capacity of interregional transmission is estimated to be 9.3GW to 10.5GW, while full strengthening of interregional transmission enables as much as 4 times integration, 32GW to 42GW (Fig. 3-1).

As the additional integration potential of each region under the current interregional transmission capacity is small, the standard deviation of hourly variation of the net load (electric load-wind power generation) when the potential is integrated does not vary significantly from the current standard deviation (Table 3-2). On the other hand, the standard deviation when the potential by strengthening interregional transmission is integrated increases from 4.55GW/h to 4.56GW/h-4.60GW/h. However, comparison with the annual average national hourly electric demand reveals that the increase in the standard deviation is negligibly small (from 4.3% to 4.4%).

The peak net load when the potential by strengthening interregional transmission is integrated is 148GW, curtailed by 6GW-7GW (peak cut) from 154GW. Meanwhile, the bottom load is curtailed by 8GW-12GW (from 66GW to 54GW-58GW), greater than the peak cut. This results from the fact that the capacity factor of wind power is as low as 16%-21% in summer when peak demand occurs and is as high as 35%-42% when the bottom electric demand occurs.

As stated above, the constraint of lack of dispatchable capacity is neglected, as the power generation mix at the bottom hour is not evident currently or in the future.

Fig. 3-1 Wind Power Integration Potential
by Strengthening Interregional Transmission (Nationwide)



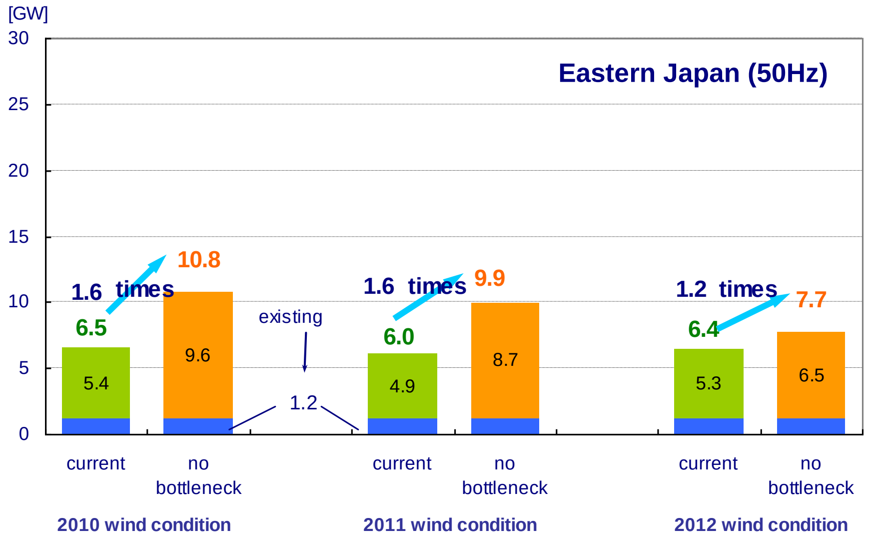
Note : The electric demand data in 2012 is used. The cumulative installed wind power is as of March 2012.
Note : "No bottleneck" means the case where the interregional transmission constraints are totally removed.

(2) Eastern and Western Japan

The government of Japan and the electric utilities are promoting buildup of frequency conversion stations with a current capacity of 1GW installed between eastern and western Japan.

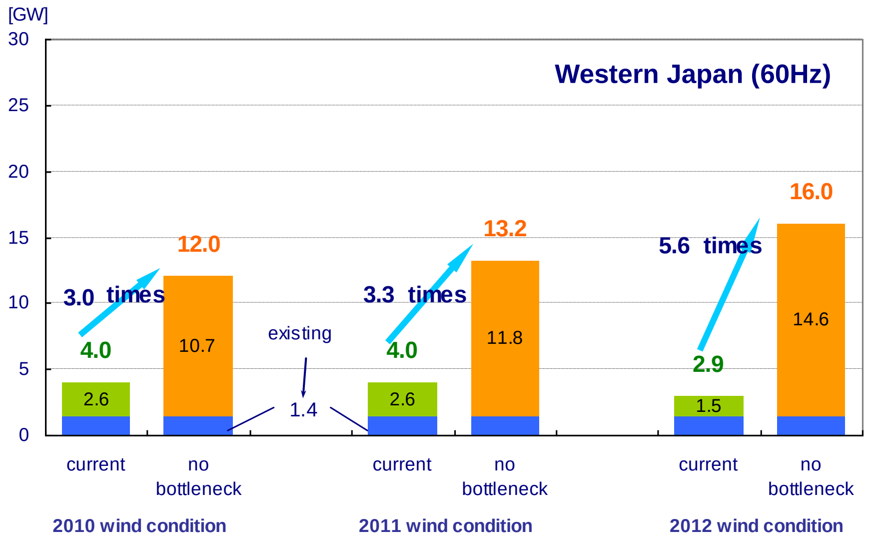
Nevertheless, the wind power integration potential is estimated when the interregional transmission lines are strengthened within eastern and western Japan individually, with an assumption that the bottleneck at frequency conversion stations may persist (Fig. 3-2 and Fig. 3-3).

Fig. 3-2 Wind Power Integration Potential by Strengthening Interregional Transmission (Eastern Japan)



Note : The electric demand data in 2012 is used. The cumulative installed wind power is as of March 2012.
Note : “No bottleneck” means the case the where the interregional transmission constraints are totally removed.

Fig. 3-3 Wind Power Integration Potential by Strengthening Interregional Transmission (Western Japan)



Note : The electric demand data in 2012 is used. The cumulative installed wind power is as of March 2012.
Note : “No bottleneck” means the case the where the interregional transmission constraints are totally removed.

In eastern Japan, the additional wind power integration potential is 4.9GW-5.4GW under the current capacity of interregional transmission lines, while strengthening of interregional transmission lines raises the potential to 6.5GW-9.6GW. Adding the existing capacity of 1.15GW, the potential increases about 1.5-fold from 6.0GW-6.5GW to 7.7GW-11GW by strengthening the interregional transmission lines. In western Japan, the integration potential including existing capacity increases 3 to 6 times from 3GW-4GW to 12GW to 16GW. In spite of a generally prevailing focus on measures to enhance the development of wind power in the northern part of Japan (Hokkaido and Totoku) by absorbing wind power generation in the Tokyo metropolitan area, this study reveals that the wind integration potential by strengthening the interregional transmission lines in western Japan is greater than in eastern Japan. In eastern Japan, absorption of wind power should highly rely on the Tokyo metropolitan area that is the only area having huge ramping capability. On the other hand, in western Japan, the ramping capability of each region is small but connecting them increases the ramping capability as a whole region (See Table 3-1). The total integration potential of eastern and western Japan is 23GW-24GW, 9GW-19GW smaller than the nationwide potential.

(3) Wind Power Generation

The annual power generation from 32GW-42GW of the wind power integration potential is 60TWh-80TWh, which equals to 6% to 8% of the annual electricity consumption. Individual strengthening of interregional transmission lines in eastern and western Japan decreases the power generation to 43TWh (Table 3-3).

Table 3-3 Annual Power Generation from Potential Wind Power Integration by Strengthening Interregional Transmission

Year of wind condition	Whole of Japan (TWh)			Eastern + Western (TWh)								
							Eastern Japan (TWh)			Western Japan (TWh)		
	As of 2012	Interregional transmission		As of 2012	Interregional transmission		As of 2012	Interregional transmission		As of 2012	Interregional transmission	
		Prst.	Str.		Prst.	Str.		Prst.	Str.		Prst.	Str.
2010	4.8	18.3	79.4	4.8	18.3	43.2	2.3	11.1	21.4	2.5	7.2	21.7
2011	4.8	16.9	71.3	4.8	16.9	43.5	2.3	9.7	20.0	2.4	7.2	23.5
2012	4.7	15.0	59.7	4.7	15.0	43.1	2.3	10.4	15.2	2.4	4.5	28.0

Note : "Prst." means present status and "Str." means strengthening of interregional transmission lines.

3-3 Wind Power Integration Potential by Power Curtailment

Strengthening of interregional transmission lines requires huge investment costs, though it is able to greatly increase the wind power integration potential according to the analysis above. Meanwhile, wind power curtailment presumably enables increasing wind power to be integrated without huge additional investment. However, how much power generation would be curtailed should be evaluated.

The wind power integration potential of each region via wind power curtailment with the current capacity of interregional transmission is estimated below. In this measure, the wind power generation that causes the events where the largest decrement of hourly net load exceeds the ramping-down capability will be curtailed. The measures to reduce electric demand such as demand response required when the net load variation exceeds the ramping-up are outside the scope of this study. As the constraint of lack of dispatchable capacity largely affects estimation results, the reduction ratio of the nationwide bottom electric demand when the potential wind power by strengthening interregional transmission is integrated (1-53.9GW/66.4GW=18% : See Table 2-3 and Table 3-2) is set as a constraint.

The additional wind power integration potential by power curtailment is shown in Table 3-4. The regional potential of many regions without curtailment was subject to the ramping-down capability (See Table 3-2), while the ramping-up capability becomes dominant in more regions by taking the curtailment measure. The additional integration potential is 13GW-17GW and is 16GW-19GW if the existing capacity is added. The curtailment measure approximately doubles the potential with the current capacity of the interregional transmission (9.3GW-10.5GW).

The curtailed hour does not exceed 50 hours a year, though it greatly varies among regions. In addition, no more than 0.1% of power generation is curtailed. The annual power generation is 27TWh-35TWh (Table 3-5).

Although there are challenging issues in terms of the practical curtailment control of how the protocol regarding how much power generation should be curtailed is to be transferred to which wind turbine, a very small fractional curtailment can yield a large increase in integration potential. As strengthening of interregional transmission lines requires huge investment costs and long lead times, it is also important that the curtailment measures be strongly addressed.

Table 3-4 Additional Wind Power Integration Potential by Wind Power Curtailment

Year of wind data	Region /Utility	Integration Potential (GW) Subject to ramping(+)	Integration Potential (GW) Subject to ramping(-)	Integration Potential (GW) The smaller	Net load when Potential is integrated: Peak demand (GW)	Net load when Potential is integrated: Bottom demand (GW)	Annual power generation (TWh/year)[1] Before curtailment	Annual power generation (TWh/year)[1] After curtailment	Curtailed hour (h/year)[1]
2010	Hokkaido	0.8	0.9	0.8	5.6	2.3	―	―	―
	Tohoku	2.7	2.2	2.2	13.4	5.3	4.48	4.48	25
	Tokyo	8.8	6.4	6.4	50.2	16.7	9.84	9.84	3
	Hokuriku	0.3	0.5	0.3	5.2	1.8	―	―	―
	Chubu	7.4	3.4	3.4	23.8	7.2	7.22	7.22	13
	Kansai	1.1	3.2	1.1	26.7	10.9	―	―	―
	Chugoku	2.2	1.8	1.8	10.6	3.6	2.77	2.76	21
	Shikoku	0.7	0.6	0.6	5.1	1.7	1.30	1.30	49
	Kyushu	0.3	3.7	0.3	15.1	5.7	―	―	―
	Total			16.9	―	―		(-0.06%)[2]	
	+existing			19.4					
2011	Hokkaido	0.5	1.0	0.5	5.6	2.6	―	―	―
	Tohoku	5.2	1.8	1.8	13.4	5.3	3.81	3.81	18
	Tokyo	10.1	6.7	6.7	50.5	16.7	9.59	9.59	3
	Hokuriku	0.7	0.6	0.6	5.3	1.7	1.28	1.28	36
	Chubu	6.8	3.5	3.5	23.9	7.2	7.42	7.42	6
	Kansai	0.1	2.8	0.1	26.8	11.0	―	―	―
	Chugoku	2.5	1.2	1.2	10.7	3.6	1.81	1.81	6
	Shikoku	0.0	0.6	0.0	5.2	2.0	―	―	―
	Kyushu	0.0	1.7	0.0	15.2	5.8	―	―	―
	Total			14.6	―	―		(-0.03%)[2]	
	+existing			17.1					
2012	Hokkaido	0.5	0.8	0.5	5.6	2.5	―	―	―
	Tohoku	4.2	2.2	2.2	13.4	5.3	4.47	4.46	23
	Tokyo	7.5	5.9	5.9	49.6	16.7	8.81	8.81	2
	Hokuriku	0.1	0.6	0.1	5.2	1.9	―	―	―
	Chubu	10.5	2.6	2.6	24.3	7.2	5.13	5.13	4
	Kansai	1.0	2.8	1.0	26.6	10.8	―	―	―
	Chugoku	0.0	1.2	0.0	10.8	4.4	―	―	―
	Shikoku	0.5	0.6	0.5	5.2	1.7	―	―	―
	Kyushu	0.3	3.6	0.3	15.1	5.7	―	―	―
	Total			13.1	―	―		(-0.03%)[2]	
	+existing			15.7					

Note 1 : Only regions where ramping-down capability is dominant are included.
Note 2 : Ratio of curtailed power generation (=curtailed power generation/power generation before curtailment)

Table 3-5 Annual Power Generation from Potential Wind Power by Curtailment Measure

Year of wind condition	(TWh) existing	Current interregional transmission lines: No curtailment	Current interregional transmission lines: Curtailment[1]
2010	4.8	18.3	34.7
2011	4.8	16.9	30.0
2012	4.7	15.0	27.2

Note 1 : Curtailment measure is taken only in the region in which ramping-down capability is dominant.

4. Concluding Remarks

This study evaluated the wind power integration potential by strengthening the interregional transmission lines and also by implementing a wind power curtailment measure in Japan.

With an assumption that totaling individual regional ramping capability yields a nationwide capability by strengthening the interregional transmission lines so that the whole of Japan can be regarded as a single system without any bottleneck at regional boundaries, the wind power integration potential was evaluated. The analysis was carried out using the regional hourly electric demand in 2012 and the hourly wind power generation at 82 locations for the last three years (2010-2012).

The wind power integration may be underestimated because the ramping capability is defined here as the capability that the aggregated power plants are able to follow the current hourly electric demand variation regarded as "business as usual" operation. On the other hand, the potential may be overestimated as the geographical distance between the dispatchable power plants and the net load is neglected. Though there still remain issues to be addressed towards detailed analysis, this study revealed that the wind power integration potential quadruples from 9.3-10.5GW with the current capacity of the interregional transmission lines to 32-42GW by strengthening the interregional transmission lines. However, the annual power generation from the potential wind power is no more than 60-80TWh, accounting for 6-8% of the annual electricity demand. If the interregional transmission lines are strengthened within eastern Japan and western Japan separately, taking into account the existing constraint at frequency conversion stations, the wind power integration potential was estimated to be 23-24GW and the annual power generation decreases to 43TWh.

Meanwhile, the wind power integration potential via a curtailment measure with the current capacity of interregional transmission lines was estimated to be 16-19GW and the annual power generation is 27-35TWh. Although the potential is smaller than the potential via the strengthening of interregional transmission lines, a very small fractional curtailment can yield a large increase in integration potential. As strengthening of interregional transmission lines requires huge investment costs and long lead times, it is important that the curtailment measures be also strongly promoted.

This study excluded an analysis on how much capacity of interregional transmission lines will be required. Estimation of the required capacity increase to enable the integration of wind power potential and analysis on the cost effectiveness comparing with the other measures such as energy storage and demand response taking into account photovoltaic integration would be future issues to be addressed.

Acknowledgements

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Appendix

Table A-1 Acceptable Wind Power

Source	(1)	(2)	(2)	(2)
	Existing(MW)	Acceptable(MW)	Existing(MW)	Rest(MW)
Hokkaido	288	560	289	271
Tohoku	697	1,580	508	1,072
Tokyo	166	―	349	―
Hokuriku	146	450	146	304
Chubu	277	―	225	―
Kansai	125	―	81	―
Chugoku	301	620	299	321
Shikoku	124	450	166	284
Kyushu	404	1,000	342	658
Total	2,528	―	2,419	―

Source : (1) comes from NEDO's "List of Installed Wind Turbines in Japan." (2) is referred from Federation of Electric Power Companies of Japan (FEPC) (http://www.fepc.or.jp/environment/new_energy/renkei/index.html).
The existing wind power is as of March 2012 and the acceptable wind power is as of July 2012.

Note : The difference in existing wind power between NEDO and FEPC might come from the fact that almost all wind turbines in Fukushima prefecture (Tohoku region) are connected to Tokyo Electric Power Company [9] and that FEPC excludes the wind power turbines that are located in remote islands not connected to the major transmission lines and also the wind turbines with constant output power.

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