Evaluation of the Optimal Power Generation Mix with Regional Power Interchange considering Output Fluctuation of Photovoltaic System and Wind Power Generation

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Overview
Due to the fossil fuel depletion and global warming, renewable energy has been attracting attention, and particularly solar power system has been highlighted. In Japan, Solar power has been introduced about 263 million kW in 2009(1). In addition, in 2009 the Ministry of Economy published "long-term energy supply and demand outlook (recalculated)"(2) and in that paper they announced that an introduction amount of solar energy in our country in 2020 will be about 20 times compared to 2,800 million kW in 2005. On the other hand, Hokkaido, Tohoku and Kyushu have a large potential in wind power. Japan Wind Power Society has set a goal of providing more than 10% from wind energy in domestic power generation mix by 2050 (3). Therefore, in the future power generation mix, solar and wind power are expected to become the center of renewable power supply sources. However, if large amounts of solar and wind power system are introduced, it will eventually cause a series of problems in stable power supply due to a lack of capacity of frequency adjustment of the output derived from rapid fluctuation, surplus power generation and rising voltage in electricity distribution system. This study, with taking into account the fluctuations in solar and wind power output, investigates the operational impact on optimal power generation mix of large renewable energy deployment and develop sensitivity analysis with respect to nuclear capacity, capability of electricity interexchange among utility companies and carbon dioxide emissions regulation. This research mainly focuses on electricity market in eastern japan, and the market is divided into three regions, such as Hokkaido, Tohoku and Kanto region. There is high potential of wind power resource in Hokkaido and Tohoku area, while Kanto region has the large electricity demand in Japan. The analysis elaborates the power system interconnection among regions and assesses the possibility of wind power introduction in the whole region.

Methods

1. Study policy

This study is carried out in the following procedures: Developing optimal power generation mix model; Calculating of operating ratio of photovoltaic system and wind power system; Analyzing optimal power generation mix model; Sensitivity analysis

2. Optimal Power Generation Mix

2.1 Model characteristics and Conditions

In this model, under various assumptions, power generation capacity and its operation are specified through the minimization of total power generation cost, mainly consisting of facility cost and fuel cost. Linear Programming method is adopted to calculate. This methodology is a specific class of mathematical problems, in which a linear objective function is either maximized or minimized subject to various linear constraints. In addition, the feature of the model developed in this paper explicitly take into consideration the intermittent output fluctuation of solar and wind energy in the time resolution of 10 minute. The model incorporates 2.5 million constraints and approximately one million variables.

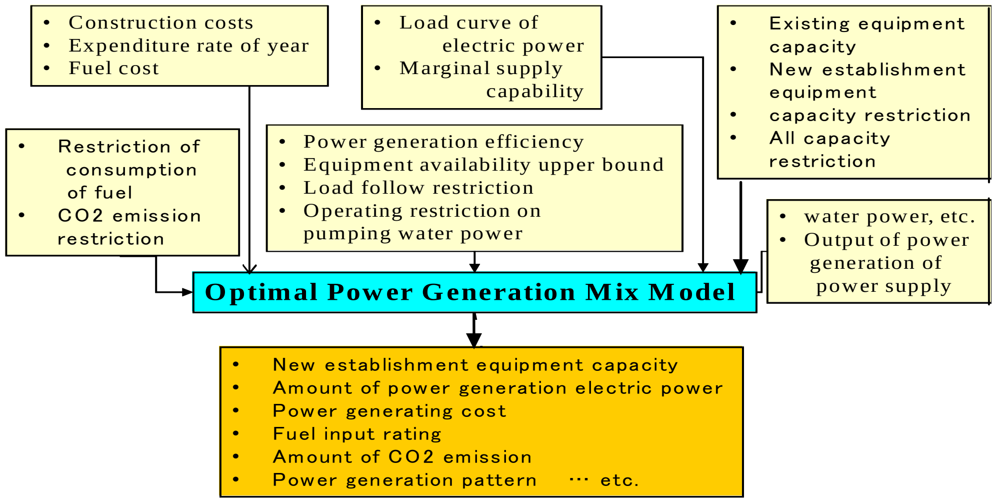


Fig.1 Flow of this model

The lower limit of power plant capacity is fixed at current installed capacity in November 2011. And the capacity of hydro, nuclear and pumped storage hydro are assumed to be exogenous variables. If not specifically noted, capacity of nuclear power plant is equal to that in November 2011. In thermal power plant, only gas (LNG) combined cycle is allowed to be increased by up to two times of current installed capacity, and other coal, oil, gas (LNG) steam power plants are fixed to the current capacity. Other power supply option, if required, is allowed to increase indefinitely.

Actual installed capacity of power transmission line between Hokkaido and Tohoku area is 0.6GW and that from Tohoku to Tokyo area is 5GW, and, from Tokyo to Tohoku, 1.3GW.In this paper, basically the upper limit of power transmission capacity is assumed to be fixed in that value. Since literature is not available describing a construction cost of power transmission line in Japan, that value is set to 0 yen/kW with inter-regional losses of power transmission lines homogeneously assumed at 0.1%.

2. 2 Making power load curve

In order to use the optimal power generation mix model which was built in this study, the electricity daily load curve is required to be arranged at every 10 minutes 365 days a year. Such detailed statistical power data, however, are not published by the government and electric utilities. As a basis for the estimation data, electricity demand patterns by company [4] and the maximum power of 365 days of each company [MW] [4] and the daily power consumption [MWh / day] [4] are employed. In this paper, some past typical power load curves (Peak, Winter working day, Winter holiday, Summer Working day, Summer holiday, Spring/Autumn working day, Spring/Autumn) are combined so that the value of its electricity demand and peak demand is equivalent to the actual observed data in each day as much as possible.

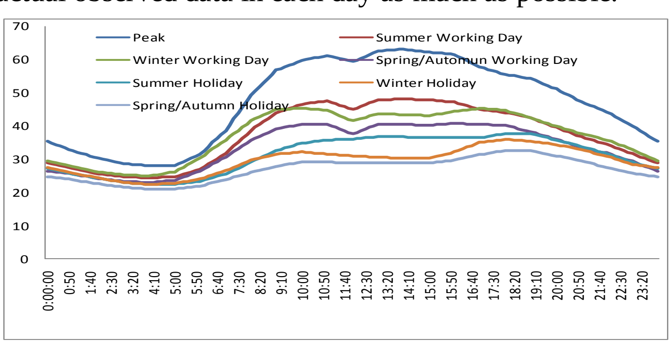


Fig.2 Pattern of demand of each season

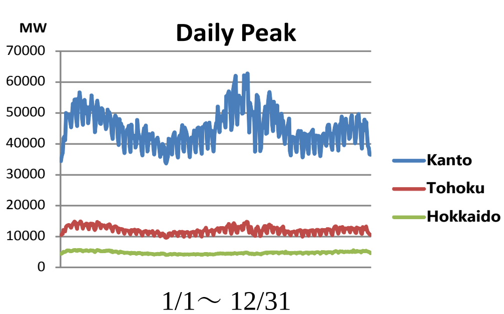


Fig.3 The daily peak

<Calculation example>

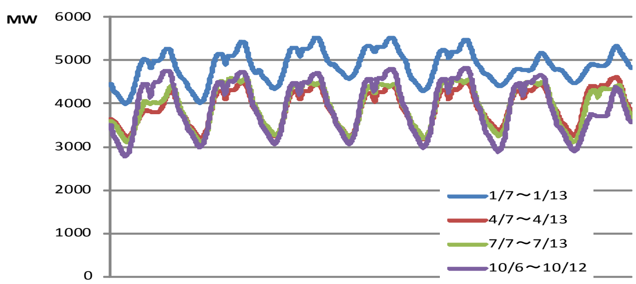


Fig.4 Power curve of Hokkaido Electric Power (2008)
[Monday to Sunday]

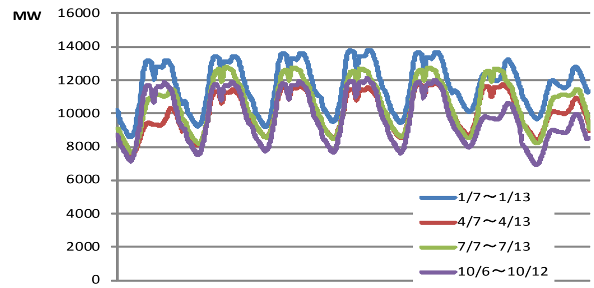


Fig.5 Power curve of Tohoku Electric Power (2008)
[Monday to Sunday]

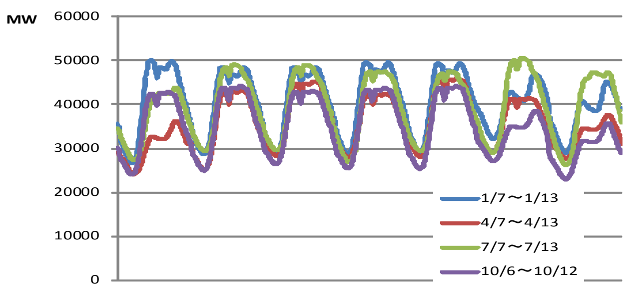


Fig.6 Power curve of Kanto Electric Power (2008)
[Monday to Sunday]

2. 3 Calculating of Operating Ratio of Photovoltaic System

The operating ratio of photovoltaic system in various places is estimated by using the model which was developed in our laboratory. The data of the quantity of solar radiation of AMeDAS(Automated Meteorological Data Acquisition System)is adopted. (latitude, longitude, altitude, sunshine duration, temperature, rainfall)
There are 223 AMeDAS's observation places in Hokkaido , 246 places in Tohoku and 136places in Kanto.
The operating ratio is calculated in the following six steps.

(1) Calculation of quantity of solar radiation of a horizontal plane
(2) Calculation of quantity of solar radiation of slope
(3) Calculation of output of power generation for each unit area
(4) Calculation of area that can be set up
(5) Calculation of PV output of power generation
(6) Calculation of PV PV operating ratio

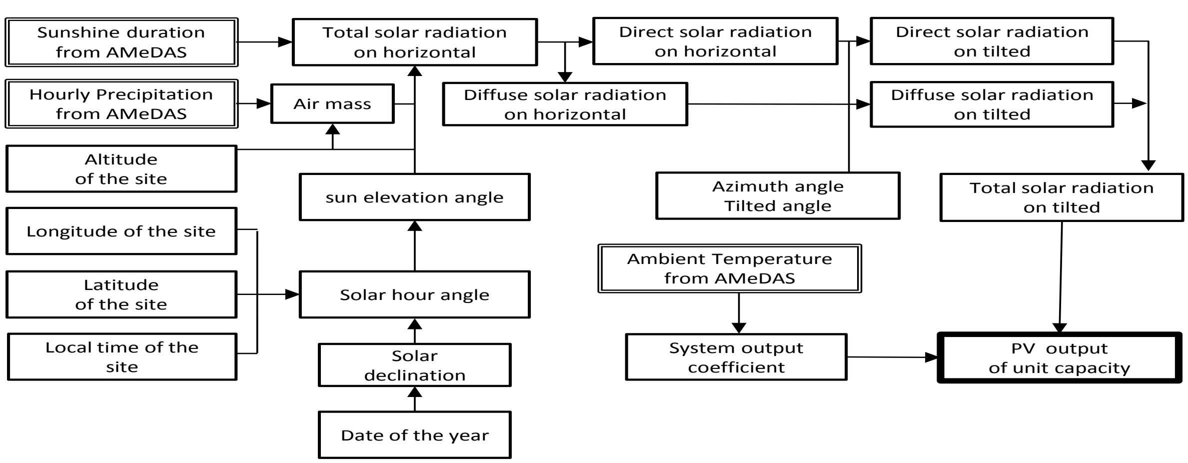


Fig. 7 Calculation flow of PV output of unit capacity for each site

First, from the data of latitude, longitude, sunshine duration and rainfall of the observation point in AMeDAS, the amount of horizontal solar radiation are determined. Estimation of the horizontal plane solar radiation are calculated based on the techniques based on literature [5] . Amount of solar radiation out of the atmosphere is calculated by solar altitude and horizontal distance between the Earth and Sun. Next, the amount of solar radiation out of the atmosphere is divided based on sunshine duration, rainfall and air mass (the amount of earth's atmosphere which the sun’s direct light passes to reach the surface of earth). However the amount of solar radiation calculated from the data of sunshine duration is the radiation on horizontal plane, so it is necessary to convert it to the radiation on inclined plane. Solar radiation on inclined surface is calculated from direct horizontal solar radiation and diffuse horizontal solar radiation which are separated from the amount of horizontal global solar radiation.

The following thee graphs are the operating ratio of Photovoltaic system in 2008. Horizontal axis is day of year from January to December. Depth axis is hour of day from 0:00 to 23:50.

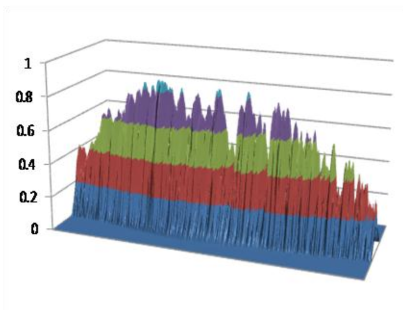


Fig. 8 Hokkaido

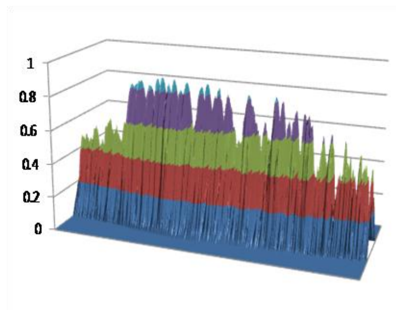


Fig.9 Tohoku

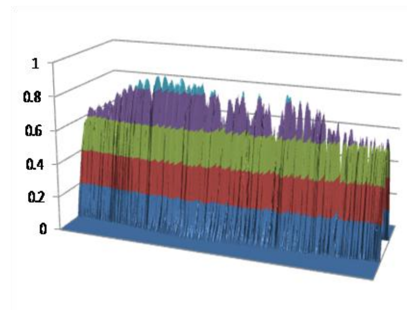


Fig.10 Kanto

2. 4 Capacity of Photovoltaic System

According to the target value[2] which has been published, the maximum capacity of PV power generation in Japan in 2020 is 28GW. Moreover, this figure, 28GW, is 20 times[2] of current situation. So, the current installed capacity is said to be 1.4GW. Therefore, for example, the ratio of total amount of PV deployment in Hokkaido is about 1%[7]compared to that of Japan, so the current installed capacity in Hokkaido is 0.014GW.And there are no upper limit.

2. 5 Calculating of Operating Ratio of Wind power generation system

Wind velocity data every 10 minutes from AMeDAS(Automated Meteorological Data Acquisition System) are used to estimate operating ratio of wind power generation system. The estimation method is like that the data of wind velocity from AMeDAS are converted into the wind velocity at hub height of general wind turbines, and from that data, operating ratio is calculated based on the wind turbine's performance curves.

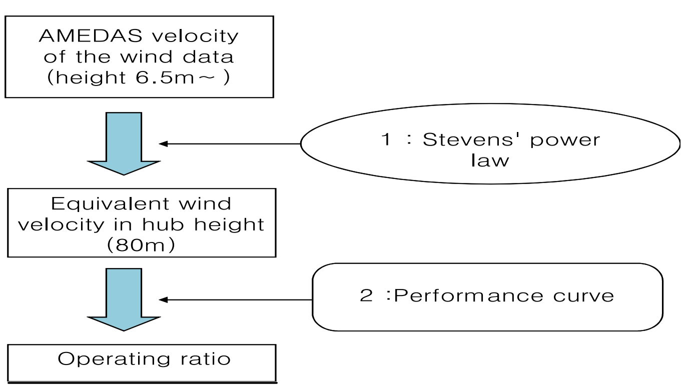


Fig.11 Flow of calculation

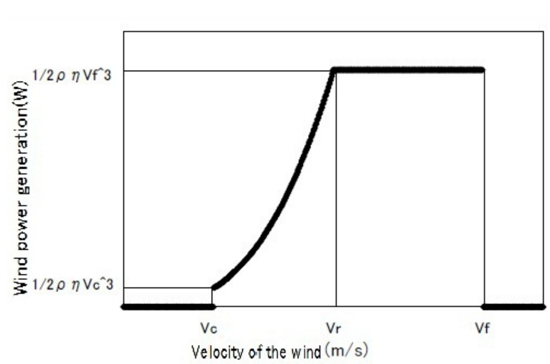


Fig.12 Performance curve

① Stevens' power law

In AMeDAS, the velocity of the wind is measured by ground high 6.5 ～10m level. Wind is stronger at the height of the hub of the pinwheel than at the near of the ground. So, the observation velocity of the wind is converted into the velocity of the wind in the height of the hub by using the following expressions.

② Performance curve

Wind energy which wind turbines capture is corresponded to the kinetic energy of air which passes through, however at the level of current technology there are no wind power generator which can use continuously all variable wind velocity. Wind turbine uses rated output as a boundary and operate differentially. Each wind turbine has a fixed value, Vc is the wind velocity which turbine starts to generate power , Vr is turbine starts rated operation, and Vf is turbine stops. The turbine doesn't generate electricity at less than the cut-in velocity or at more than the cut-out velocity. The relation between the velocity of the wind and the output of power generation is fig.12.In this study, power generation in a large wind turbine is expected so the values are set such as Vc=5, Vr=12.5, and Vf=25(m/s). Velocity of the wind Vr that becomes the state of max power is called a rated wind velocity, and availability becomes 1.00 at this time.

The following thee graphs are the operating ratio of wind power generation system in 2008. Horizontal axis is day of year from January to December. Depth axis is hour of day from 0:00 to 23:50.

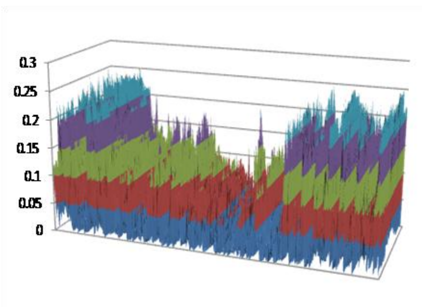


Fig.13 Hokkaido

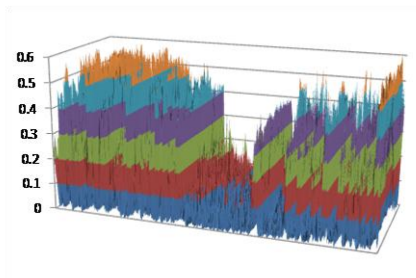


Fig.14 Tohoku

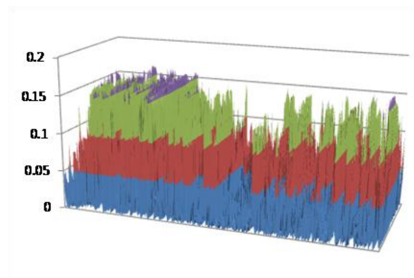


Fig.15 Kanto

From the data of the place which wind turbines actually exist, using data of AMeDAS is determined.

2.6 Capacity of wind power generaiton system

Wind power potential is very large in the Eastern Japan, but it is difficult to use them all because it is necessary to consider the geographic location of wind turbines. Therefore, the upper limit of the amount of wind power generation was determined based on the scenarios presented by the Ministry of the Environment [8] .

3.Results

3.1 Case setting

Sensitivity analysis is conducted in following ingredients:

①Capacity of nuclear power plant

②Capacity of electricity transmission line and carbon dioxide emissions constraint

③Transmission line between Hokkaido and Kanto, and carbon dioxide emissions constraint

3.2 Capacity of nuclear power plant

After the East Japan earthquake that occurred in March 2011, nuclear power plant shut down one after another. Also, after the earthquake, some plants which are under regular inspections are not permitted to restart operation. Therefore, it needs that the impact of the reduction of nuclear power plant capacity on optimal power generation mix is investigated.

This time, the following three patterns are analyzed.

- ●Capacity before the earthquake
- ●After the earthquake1 （The case that nuclear power plant which is currently down for maintenance will be start again at any time during the next fiscal year.）
- ●After the earthquake2 (The case that nuclear power plant which is currently down for maintenance will not start never again）

The following thee graphs are the annual generation in 2008.

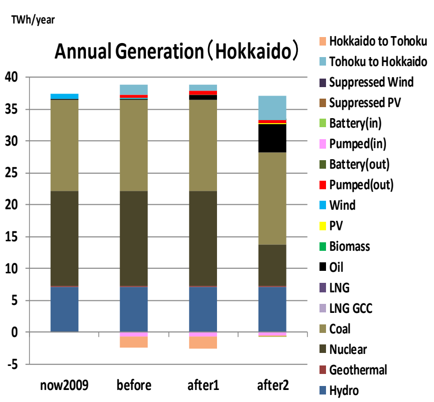


Fig.16 Hokkaido

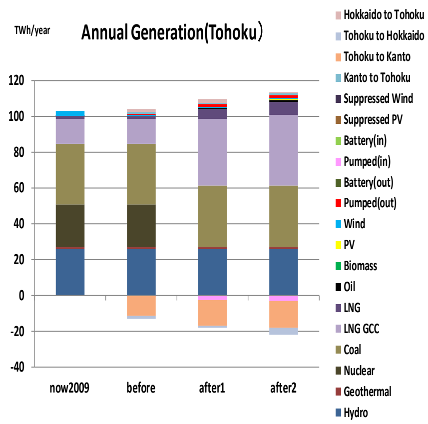


Fig.17 Tohoku

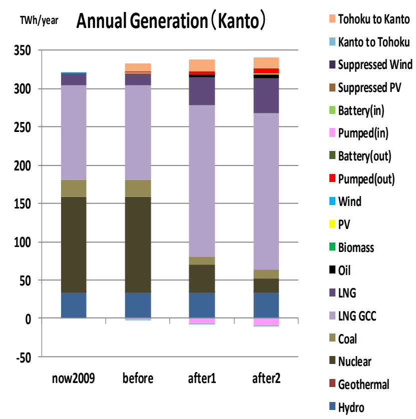


Fig.18 Kanto

In Kanto and Tohoku, after the earthquake many of the nuclear power plant shut down, LNG GCC is mainly introduced instead of nuclear power plant. In addition, it shows that the scale of electricity transmission from Tohoku to Kanto is approximately 1.9 times the current amount of transmission. However, wind power generation is not so much deployed because it costs very high compared with other power supply option.

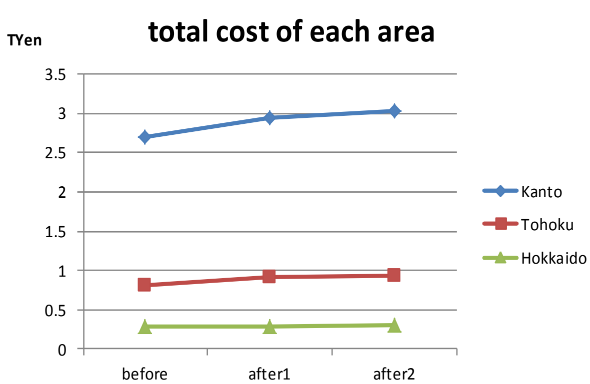


Fig.19 Total cost of each area

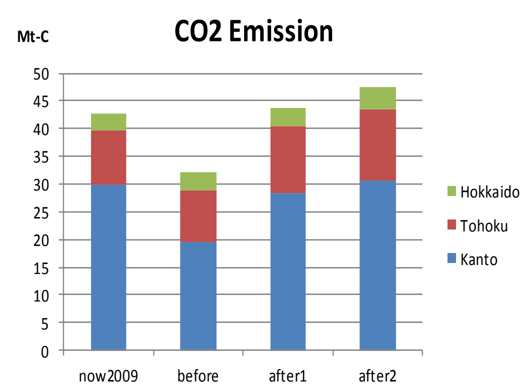


Fig.20 CO2 Emission

After the earthquake, system costs increase mainly due to more introduction of thermal powers, and the increase is approximately 1.1 times in any region. At the situation of before the earthquake, it is possible to decrease the emission compared to the actual value of 2009. However, at the situation of after the earthquake, the emission increases due to the replacement of nuclear by thermal power plants. If the situation of "after2" continues, will increase by approximately 30% compared to that of 2009.

3. 3 **Capacity of transmission line and carbon dioxide emissions constraint**

In this section, the effects of capacity constraint on electricity transmission are analysed under following three assumptions.

●There is no power transmission.

●The upper limit of the capacity of transmission line corresponds to the current scale of the capacity.

●There is no upper limit of the capacity of transmission line. Transmission line can be freely expanded.

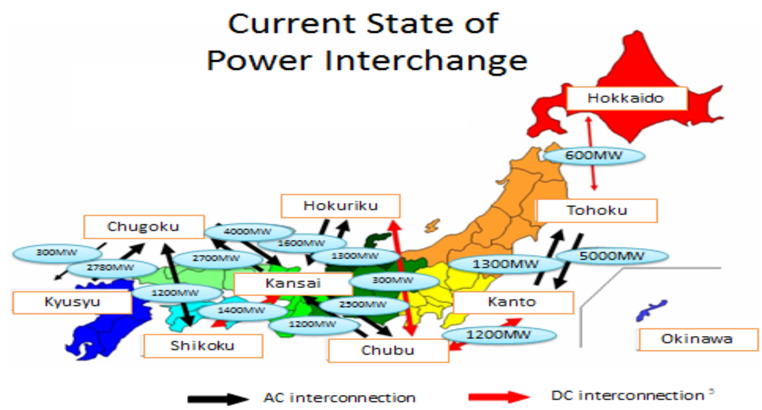


Fig.21 Current state of power interchange

At the same time, the impact of carbon dioxide emissions constraints is analysed in following four regulation assumptions.

◆ There is no constraint.

◆ -25% compared to 1990

◆ -60% compared to 1990

◆ -80% compared to 1990

The above carbon regulation is assigned on the entire 3 areas, and the calculated percentage of the reduction is different by region.In addition, when the emission reduction is achieved, electricity demand saving is considered to be implemented. Therefore, at the case of “-25%”, “-60%” and “-80%”, the value of the load curve is decreased by 15% homogeneously at each time step, and it is used for the simulations.

<There is no power transmission.>

The following thee graphs are the annual generation in 2008.

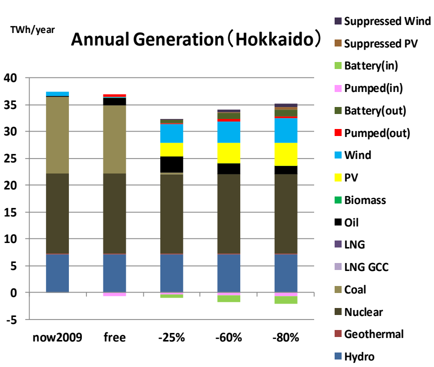


Fig.22 Hokkaido

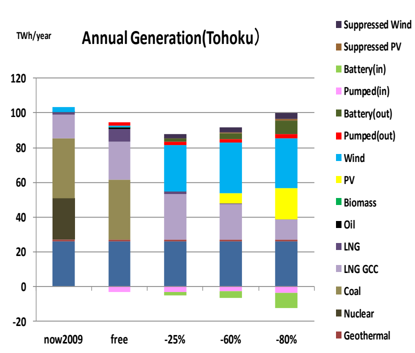


Fig.23 Tohoku

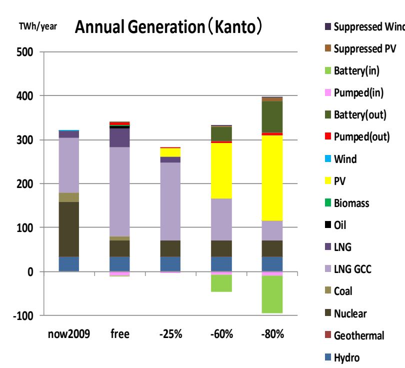
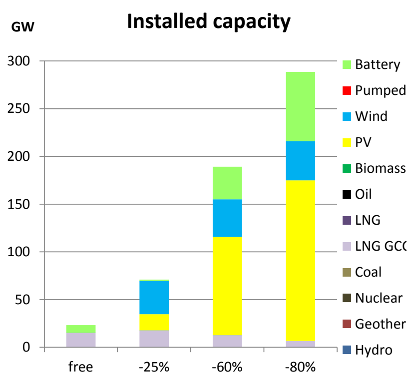
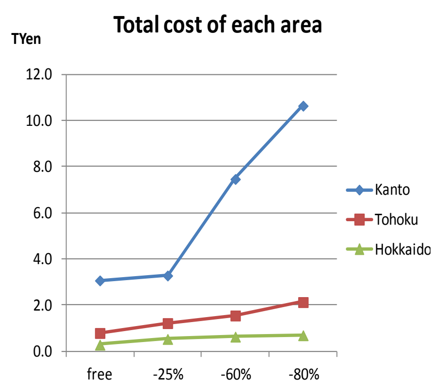


Fig.24 Kanto

When the carbon dioxide emission constraint becomes harder, the capacity of renewable energy such as solar and wind is increased. Especially in Tohoku, first the capacity of coal decreases and next the capacity of LNG GCC decreases. This is because that the fuel cost and the construction cost of Coal plant is more expensive than that of LNG GCC. After that, first wind power which is low cost is introduced, next solar power is introduced. Incidentally, from "free" to "-25%" the introduction of large amounts of wind in Tohoku contributed significantly to reducing CO2 emissions, and from "-25%" to "-60%" the introduction of large amounts of PV in Kanto contributed significantly.





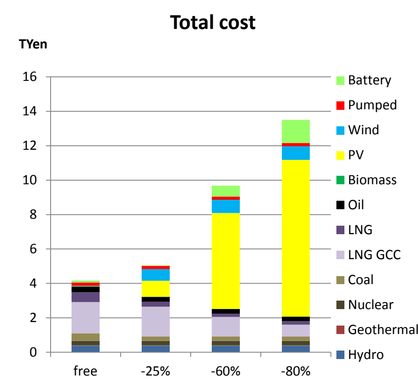
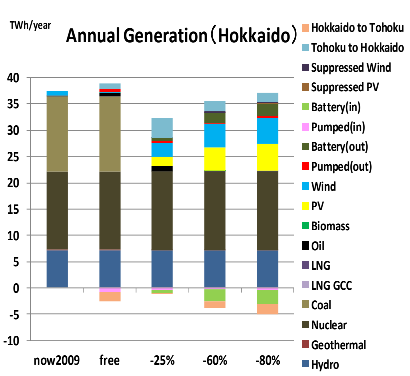


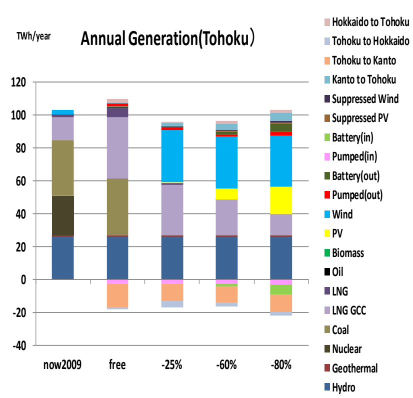
Fig.25 Installed capacity (3areas) Fig.26 Total cost of each area Fig.27 Total cost (3areas)

At all areas the costs tend to increase , and especially Kanto area shows the largest increase. This is principally due to the significant introduction of photovoltaic power as shown in Fig.24.

<The upper limit of the capacity of transmission line is current capacity>

The following thee graphs are the annual generation in 2008.





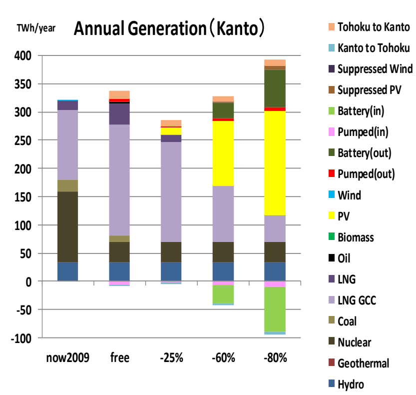
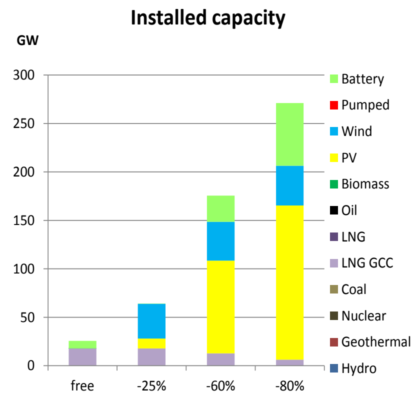
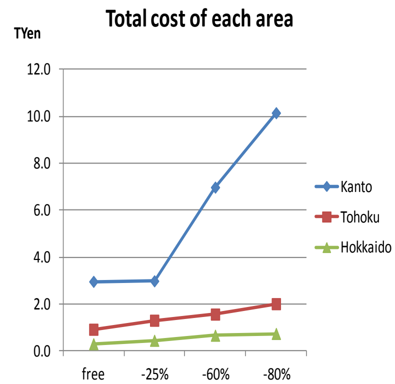


Fig.28 Hokkaido Fig.29 Tohoku Fig.30 Kanto





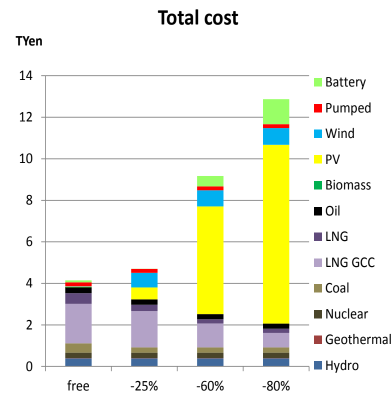
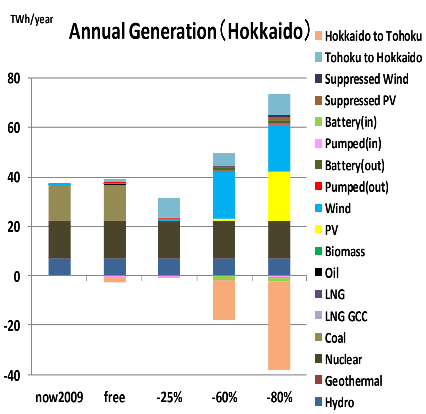


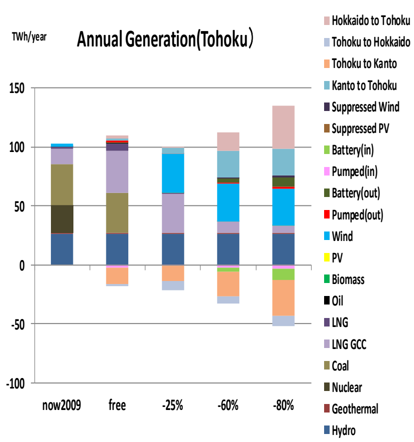
Fig.31 Installed capacity (3areas) Fig.32 Total cost of each area Fig.33 Total cost (3areas)

At this situation, the results are similar with the results of above situation of "no transmission line". In addition, Kanto area received power from other areas, so the amount of cost in Kanto slightly decreases compared to the cost of the situation of "no transmission line".

<There is no upper limit of the capacity of transmission line.>

The following thee graphs are the annual generation in 2008.





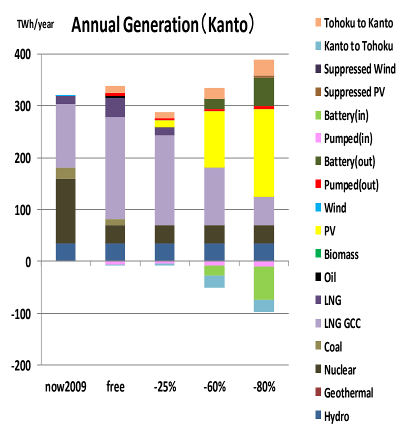
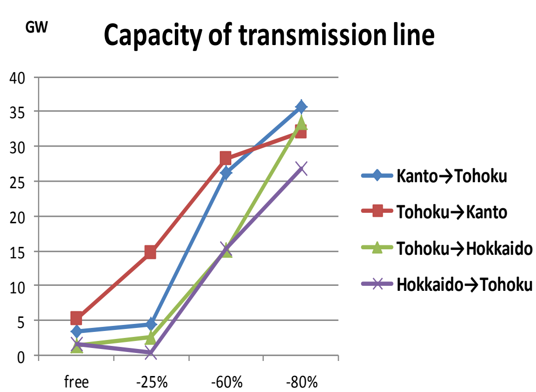


Fig.34 Hokkaido Fig.35 Tohoku Fig.36 Kanto



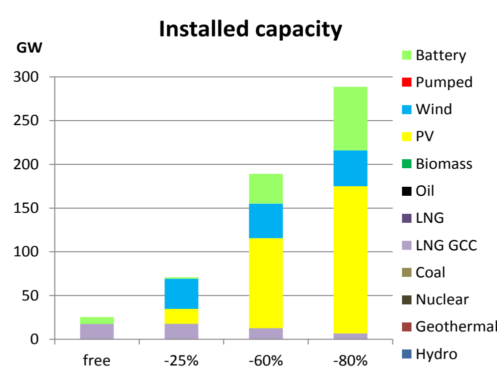
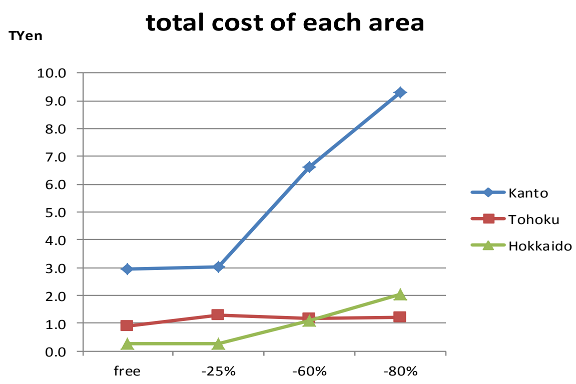


Fig.37 Capacity of transmission line Fig.38 Installed capacity (3areas)



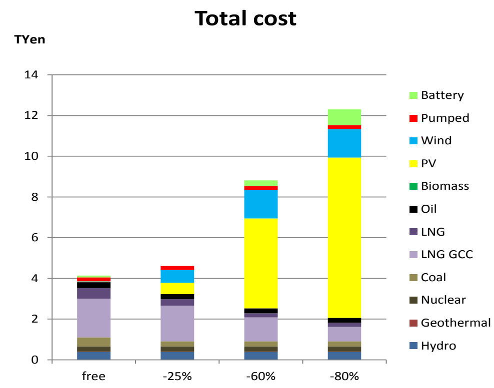


Fig.39 Total cost of each area

Fig.40 Total cost (3areas)

At the situation of "no upper limit of transmission", the scale of regional electricity transmission significantly increases. Especially the amount of power transmission from Hokkaido to Kanto shows the largest growth. In terms of the added capacity of transmission line, it increases about 6 to 50 times compared to the current value of capacity. The flow of electricity is observed from Hokkaido to Tohoku, and from Tohoku to Kanto. Furthermore, since in Tohoku the amount of received power significantly increase, so PV is not introduced furthermore.

3. 4 Transmission line between Hokkaido and Kanto, and carbon dioxide emissions constraint

Eastern 3 utility power companies (Hokkaido, Tohoku, Tokyo), on 30 September 2011, announced a project to conduct experiments to adjust the output of renewable energy such as wind power by cooperating each other. To develop and utilize large amounts of unstable renewable energy such as wind, it is essential to do regional cooperative management of power system. The aim of this experiment is to expand wind power capacity in Hokkaido and Tohoku regions by using the enough capability of Kanto region to adjust the intermittent output of wind power in those both regions. For this experiment, Hokkaido electric company are ready to install the wind capacity of 0.2GW, and Tohoku electric company, 0.4GW. The impact of this experiment on the regional optimal power generation mix is simulated in this chapter. Under this situation, several capacity values of transmission line from Hokkaido to Kanto are assumed in following three cases. This calculation assumes that regional carbon dioxide emissions is regulated by 25% from its 1990 level and electricity demand is mitigated by 15% from the reference demand.

Table1. Case setting

		Hokkaido to Tohoku	Hokkaido to Kanto	Tohoku to Hokkaido	Tohoku to Kanto	Kanto to Tohoku
case1	max	0.6	0	0.6	5	1.3
	min	0	0	0	0	0
case2	max	0.6	0.1	0.6	5.2	1.3
	min	0	0.1	0	0.2	0
case3	max	0.6	0.2	0.6	5.4	1.3
	min	0	0.2	0	0.4	0
						(GW)

The following thee graphs are the annual generation in 2008.

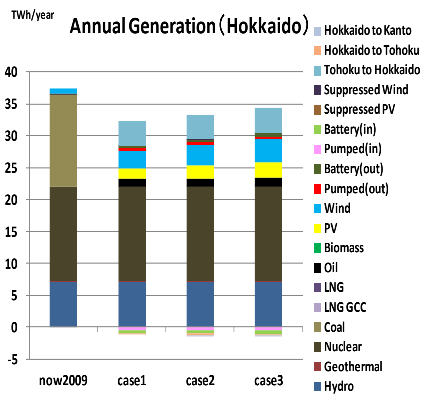


Fig.41 Hokkaido

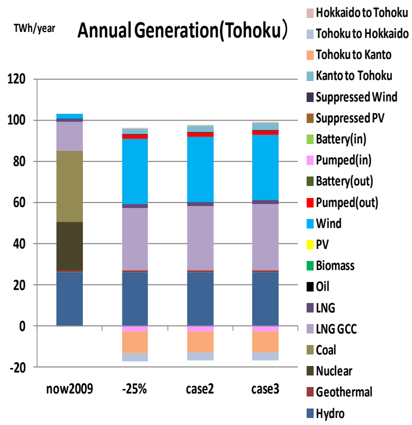


Fig.42 Tohoku

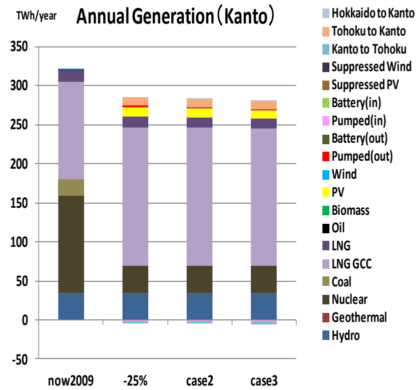


Fig.43 Kanto

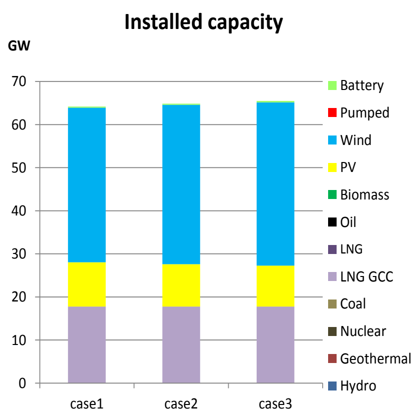


Fig.44 Installed capacity (3areas)

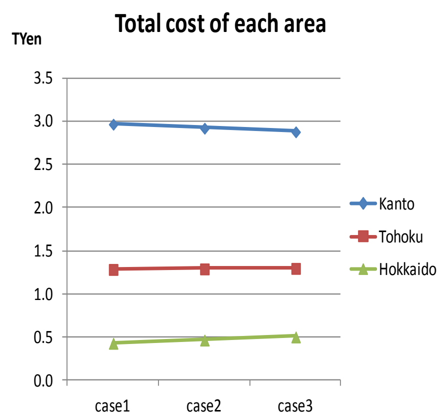


Fig.45 Total cost of each area

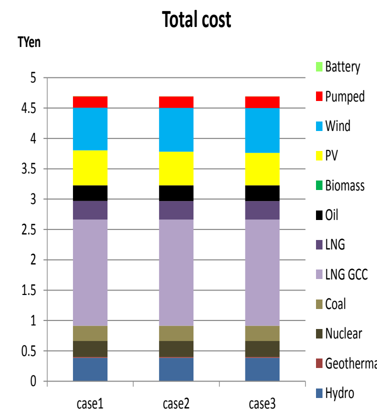


Fig.46 Total cost (3areas)

There is no significant change in power generation mix if transmission lines from Hokkaido or Tohoku to Kanto are expanded about 0.2GW or 0.4GW. However, actually in Kanto the amount of capacity of PV system decreases, and in Hokkaido the amount of capacity of wind gradually increases. Therefore, if the capacity of transmission lines will increase further, the capacity of wind energy will also increase moreover. Calculated results shows that cost tend to change as well. In Kanto area, the cost is observed to decrease. On the other hand, in Hokkaido and Tohoku area, the cost increases by contrast. As a whole, total regional cost of three areas slightly decreases. In this simulation, however, the cost of construction cost of transmission line is not considered. If it is considered, therefore, the cost is supposed to increase further.

Conclusions

As a result of simulating the power supply situation after the earthquake, thermal power generation such as coal-fired and LNGCC are deployed greatly in place of nuclear, which consequently causes the soaring in carbon-dioxide emissions by around 30 percent. Additional measures will be indispensable to reduce carbon dioxide emissions if nuclear continue to be stranded.

On the other hand, it is potentially confirmed in our analysis that wind power generation is effectively adopted through regional power interchange which leads to the carbon dioxide reduction in Eastern Japan. As additional important finding, PV system, a higher cost power supply option, is introduced in large quantities in Kanto region if a carbon dioxide regulation is severely arranged, therefore it suggests that the introduction of PV system will progress even more under the further cost reduction backed by the future technological advancement.

Regarding the attempts to send renewable energy, wind power in particular, to Kanto from Hokkaido and Tohoku regions, if the experiment is done at the level of the capacity which is suggested now, there is no significant change of cost and the capacity of wind and PV increases, although this may be a good method of carbon dioxide reduction. However, it is necessary to consider the construction cost of transmission lines, and the capacity of transmission lines will be limited if large wind resources in Tohoku and Hokkaido is effectively consumed in Kanto area. Willingness to try to reduce carbon dioxide all over the East Japan, however, is environmentally benign attempt, and further research to realize it will be expected.

As our future agenda, more detailed technological description of power system is required particularly under massive adoption of intermittent renewables. When PV and wind power generation are introduced widespread in the system with a steep weather condition, it is expected that it negatively influences on the voltage, the frequency and the stabilization of the power supply system. Therefore, it is necessary to develop a model which incorporates the technological impact of widespread renewable energy on the stabilization of power system.

Moreover, now in the Western Japan the use of nuclear power plant is also refrained, and some plants are maintenanced or stranded. And because of this, the optimal power generation mix in West Japan also changes. Therefore, it is necessary to consider the power interchange between all areas in Japan and analyze the optimal power generation mix of the entire Japan including the Western part.

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