# Analysis of Post-2030 Power Generation Mix with Model Considering Control Reserve and Policy Implications

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In this paper, we analyze power generation mix after 2030 with model considering control reserve. The current amount of renewable energy approved by FIT are unevenly distributed in Japan. If we assume that renewable energy will be expanding at the current growth rate, a total amount of renewable energy may be subjected to the system constrains including control reserve and capacities of interconnection in the future. The results illustrate regional differences of 9 Electric Power Companies. Local areas, which already have many renewable energy facilities, will reveal their limits to incorporate further renewable in their power system even with some amount of energy storage system. In urban areas such as Tokyo Electric Power Co., there will be room for additional introductions of intermittent renewable energy. We also describe policy implications based on the analysis results. Future energy policies should consider projections of power system reserves in detail and technological developments to encourage stakeholders to realize optimal renewable energy mix and achieve GHG emissions target in 2050.

***Keywords***: Power Generation Mix, FIT, Battery, Renewable

## 1. Introduction

Japan's first Strategic Energy Plan since the Great East Japan Earthquake was approved in July 2015. At the same time, Japan released its Long-term Energy Supply and Demand Outlook[1)], which contained the country's future energy mix, including power generation mix. The Long-term Energy Supply and Demand Outlook presents the power generation mix for 2030 and the government's various policies, too, consider this mix as one target. For example, Japan's feed-in tariff (FIT) for renewable energy is being promoted as a policy guaranteeing the long-term purchase of energy for 20 years. Looking at the current situation of certification, renewable energy has increased to a point where it is close to the target for 2030 laid out in the Long-term Energy Supply and Demand Outlook. Meanwhile, there is growing momentum for revising this policy, including introducing bidding for photovoltaic generation for renewable energy to FIT, given rising uncertainty about the outlook for the restart and new construction of nuclear power plants as well as the outlook for thermal power plants after 2030. To achieve the target for 2050 and long-term targets thereafter, consideration must be given to the development of various power generation sources and the introduction of renewable energy, with regard to the power generation mix for 2030 and beyond. Based on this, policies that will have a long-term affect such as FIT must also be examined simultaneously.

In this analysis, we describe policy issues by analyzing Japan's power generation mix after 2030 with a model for power generation mix considering control reserve as analysis for contributing to the above.

## 2. Japan's Future Power Generation Mix

### 2.1 Analysis of Future Power Generation Mix

A large number of analyses have been carried out on the power generation mix for 2030 presented in the Long-term Energy Supply and Demand Outlook approved in 2015. The Fujii-Komiyama Laboratory (2016)[2)] of The University of Tokyo calculated the optimization of amounts of photovoltaic power generation introduced by location using a detailed model of power generation mix, which revealed that the closer to cost minimization the more photovoltaic power generation would increase in and the control areas of Tokyo Electric Power Company and Chubu Electric Power Company because of electricity demand and control reserve volume. Yamamoto (2014)[3)] pointed out that even when increasing the amount of

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photovoltaic and wind power for 2030 in order to control peak demand during the early evening hours of winter and restrict the need for LFC, the effects of substituting other grid system generation facilities are small. Also, Ogimoto (2017)[4] examined electricity supply and demand for 2050, with 2030 as a mid-way point, carrying out an analysis on the necessary amount of thermal power, the amount of curtailment of renewable energy and the amount of battery power systems and hydrogen.

## 2.2 Key Points of Future Power Generation Mix After 2030

Regarding renewables, there is little basis currently suggesting that the introduction of renewable energy will advance in the power generation mix for 2030 and beyond given the current reviews of FIT. Also, taking into account the current plan, the same can be said for thermal and other power generation facilities as the outlook for 2030 and beyond appears challenging and there is a high degree of uncertainty about the necessary control reserve of LFC as a power system. If thermal power declines and variable renewable energy increases, this could have an impact on the introduction amounts given control reserve constraints.

In this analysis, we carried out an analysis considering the LFC control reserve based on the power generation plan that can be forecast now and the supply and demand situation of each region with regard to the power generation mix for 2030 and beyond.

# 3. Methodology

## 3.1 Summary of Power Generation Mix Model

In this analysis, we developed an analysis model referencing the model of the Fujii-Komiyama Laboratory (2016)[2], which is a model for power generation mix for detailed analysis by time and by location taking into account the joint research of the Institute of Energy Economics Japan and the Fujii-Komiyama Laboratory.

This model uses linear programming to optimize economically rational electricity supply and demand that minimizes total generation costs. This model includes supply-demand balance constraints, installed capacity constraints and interconnection constraints as the main constraints, and in this analysis, we decided to particularly take into account the LFC control reserve as well. The main constraint condition formulas are indicated below. Refer to the Fujii-Komiyama Laboratory (2016)[2] for other details.

**・Objective function**

$$TC = \sum_{i=1} (g_i \times pf_i \times K_i + \sum_{d=1}^{365} \sum_{t=1}^{24} pv_i \times X_{i,d,t}) + \sum_{j=1} CS_j + ECO2 \times ctax \quad (1)$$

g i: annual expense ratio of power source i, pf i: construction cost of power source i
K i: installed capacity of power source i, pv i: fuel cost of power source i
X i, d, t: utilization amount at d day and t time of power source i
CS j: electricity storage facility costs of j
ECO2: CO2 emissions, ctax: carbon tax

**・Supply-demand balance constraint**

$$\sum_i X_{i,d,t} + \sum_j (Dis_{j,d,t} - Cha_{j,d,t}) + \sum_b cc_{n,b} \times (Tp_{b,d,t} - Tn_{b,d,t}) - Loss_{n,d,t} = Load_{n,d,t} \quad (2)$$

Dis j, d, t: discharging amount of d days and t for electricity storage of j
Cha j, d, t: charging amount of d days and t for electricity storage of j
cc n, b: connectivity matrix of n and branch b,
Tp b, d, t: electrical receiving amount at branch b for d days and t
Tn b, d, t: electrical discharge amount at branch b for d days and t
Loss n, d, t: electrical discharge loss (loss of half each for each end node of branch)
Load n, d, t: demand for d days and t of n node

**・LFC control reserve constraint**

We formulated the LFC control reserve constraint as below referencing Yamamoto (2014) [3]. Control reserve constraints are for each area and do not consider accommodation to outside areas.

$$LFCD_{area} = \sqrt{(0.1 \times \sum_n PV_{n,d,t})^2 + (0.15 \times \sum_n \frac{windmw_n}{wind_{n,d,t}} WIND_{n,d,t})^2 + 2.77 \times 10^{-5} \times (\sum_n Load_{n,d,t})^2} \quad (3)$$

LFCD area: required LFC amount within the area
PV n, d, t: PV generation amount for d days and t time of n node
wind n, d, t: wind power generation amount prior to curtailment of d days and t time of n node
wind mw n: installed capacity of wind power of n node
WIND n, d, t: wind power generation amount after curtailment of d days and t time of n node

The formula (3) is linear approximation following Yamamoto (2014)[3].

$$LFCS_{area} \le \sum_i (lfc_i \times X_{i,d,t}) + \sum_j (lfc_j \times Dis_{j,d,t} + lfc_j \times Cha_{j,d,t}) \quad (4)$$

LFCS area: LFC supply amount within the area
lfc i: LFC control ratio of utilization amount of power source i
lfc j: LFC control ratio of utilization amount of electricity storage facility j

The ratio of LFC control reserve of the operation amount in the formula (4) is a uniform 5% for thermal power and a uniform 20% for battery power systems including pumped storage.

## 3.2 Assumptions

### (1) Scope of Analysis

The analysis was carried out separately for the East Japan Area (64 locations) and the West Japan Area (71 locations) (excluding Okinawa Electric Power Company). The target year is the one-year period of 2040 and the unit of time is one hour. The scope of optimization is the operational pattern of each power generation facility as well as the capacity of photovoltaic power generation and wind power generation and the capacity of battery power systems.

### (2) Electricity Demand

Referencing the demand value of 881.2 billion kWh (demand end) assumed[5)] by the Cross-regional Grid Development Commission for 2030 taking into account the long-term outlook, electricity demand is expected to remain flat until 2040. Adding a 3% loss to this figure, we assumed that Japan's overall grid demand is 907.6 billion kWh. We referenced the Fujii-Komiyama Laboratory (2016) [2)] for demand patterns by location.

### (3) Thermal Power Generation and Pumped Storage

We assumed future power generation facilities by referencing the electricity supply plan of OCCTO, press releases of power companies, environmental assessment data of the Ministry of Economy, Trade and Industry and the Ministry of the Environment, and information of the KIKO Network. The generation facilities are assumed to be decommissioned after 45 years in service.

### (4) Nuclear Power Generation

We assumed the installed capacity for achieving the nuclear power generation share in the long-term outlook for 2030. The facilities that will be operational continuously until 2040 include 10 GW in East Japan and 16 GW in West Japan, for an assumed facility utilization rate of 80%.

### (5) Energy Prices

Referencing the IEA's (2016)[6)] New Policy Scenario, we assumed that in 2040 the oil price will be $124/bbl, natural gas $12.4/MMBTU, thermal coal $80/t and the exchange rate ¥120/$

### (6) Renewable Energy

Based on the value for 2030 of OCCTO assumptions[5)] (Scenario [1]) referenced in the long-term outlook, we assumed a linear increase until 2040 based on the increase from today until 2030. In particular, we defined photovoltaic power generation and wind power generation as variable renewable energy and established an upper limit on the amount of both that could be introduced as part of scenario analysis. We referenced the Fujii-Komiyama Laboratory (2016)[2)] for power output patterns by location for photovoltaic power and wind power.

### (7) Battery Power Systems

We established an upper limit for the amount of battery power systems that could be introduced for each location by each scenario and assumed the future cost referencing the NEDO outlook[7)].

### (8) Interregional Interconnection of Power Grids

For the operation capacity of interconnections, we referenced the value for fiscal 2026 of the operation capacity of interconnections between fiscal 2019 and fiscal 2026 (long-term plan)[8)]. Enhancements to interregional interconnections considered Hokkaido–Honshu HVDC Link and Tohoku-Tokyo HVAC Link where plans are now progressing as of October 2017, and it was assumed that these would simply be added to the operation capacity. With respect to the margin for the interconnection line, we assumed that the Hokkaido–Honshu HVDC Link has 0.6GW.

## 3.3 Scenario Assumptions for Analysis

We carried out the scenario analysis which has setting an upper limit for the amount of variable renewable energy and upper limit for battery power systems. The scenarios and overview of settings can be found in **Table 1**.

**Table 1 – Scenarios and Overview of Settings**[1]

(Same for East Japan Area and West Japan Area)

| Scenarios | Upper limit of variable renewable energy installed capacity | Upper limit of battery power system installed capacity by location |
|---|---|---|
| **(1): 1x & 0.2GW** | Linear increase from 2030 outlook to 2040 | 0.2GW |
| **(2): 1.5x & 0.3GW** | 1.5x (1) | 0.3GW |
| **(3): 2x & 0.5GW** | 2x (1) | 0.5GW |
| **(4): 3x & 1GW** | 3x (1) | 1GW |

## 4. Results

### 4.1 Power Generation Mix by Area

The following describes the analysis results for each scenario indicated in 3.3. Power generation of variable renewable energy will increase in the East Japan area following the increase in the upper limits of capacity for variable renewable energy and battery power systems (**Figure 1**). However, even when doubling the upper limit of variable renewable energy, the power generation amount will not double because of supply demand constraints and control reserve constraints of each area; therefore, measures are needed to alleviate constraints including adding battery power system capacity in order to expand renewable energy further. An increase in variable renewable energy could cause a shutdown of nuclear power plants because it is not easy for nuclear to control the output flexibly in Japan, and output controls will be needed even for controllable renewable energy such as biomass. As the introduction amount of variable renewable energy increases, other low carbon power sources will be forced to carry out output controls, indicating the possibility for competition between low carbon power sources.

[1] The scale of the battery power system facilities in the demonstration testing projects currently underway are as follows. Minamihayakita of Hokkaido Electric Power Company 0.015 GW, Nishisendai of Tohoku Electric Power Company 0.02 GW, Minamisoma of Tohoku Electric Power Company 0.04 GW, and Buzen of Kyushu Electric Power Company 0.05 GW.

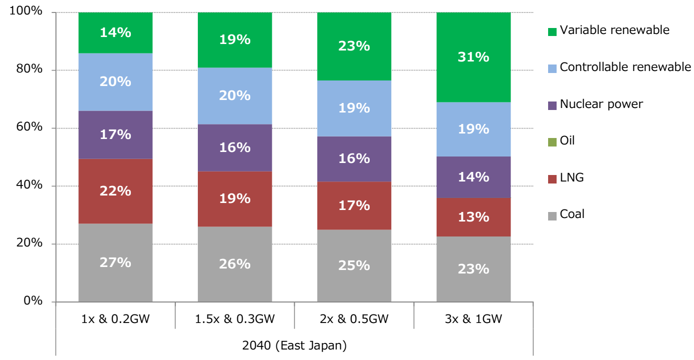


**Figure 1 – Power Generation Mix for 2040 in the East Japan Area by Scenario**

For the West Japan Area, similar to the East Japan Area, the results indicated that even when increasing the upper limit of variable renewable energy, the power generation amount will not increase by the same amount due to various constraints. (**Figure 2**)

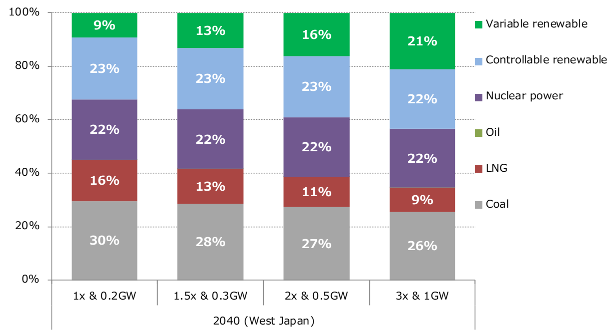


**Figure 2 – Power Generation Mix for 2040 in the West Japan Area by Scenario**

### 4.2 $CO_2$ Emissions Coefficient

The $CO_2$ emissions coefficient for 2040 for grid electricity excluding private power generation is between 0.24 and 0.31kg-$CO_2$/kWh in the East Japan Area and between 0.26 and 0.31kg-$CO_2$/kWh in the West Japan Area. The $CO_2$ emissions coefficient for fiscal 2013 released by the Federation of Electric Power Companies was 0.567kg-$CO_2$/kWh. The results of this calculation are on a calendar year basis, and while the scope of electric companies does not completely match the scope of electric companies included in the data of the Federation of Electric Power Companies. As reference for comparison purposes, the results of this calculation represent a reduction of between 46% and 58% of the $CO_2$ emissions coefficient for fiscal 2013 released by the Federation of Electric Power Companies.[2]

[2] The Action Plan for the Electricity Business for Achieving a

### 4.3 Introduction Amounts of Renewable Energy and Battery Power Systems by Region

As indicated in the previous section, given the supply-demand balance and control reserve constraints, simply increasing the upper limit of the introduction amount of variable renewable energy will not mean that the power generation amount of variable renewable energy will increase along with this upper limit.

**Figure 3** contains the installed capacity of variable renewable energy and the introduction amount of battery power systems in the East Japan Area, while **Figure 4** and **Figure 5** indicate the introduction amounts of variable renewable energy and battery power systems in each power company control area. The introduction of variable renewable energy will continue in the Tokyo control area within the East Japan Area, but it will not increase by a similar amount in the Hokkaido and Tohoku control areas. This is believed to be because this analysis assumed the amount of variable renewable energy that can be introduced mainly in locations that are appropriate at the present time, and reflects the geographic characteristics of the grid situation. Battery power systems will be introduced at an increasing pace as a measure for promoting the expansion of variable renewable energy together with the upper limit in the Hokkaido and Tohoku control areas, but the same will not happen in the Tokyo control area. As a result, there is a possibility that the cost burden of grid countermeasures will vary largely by region.

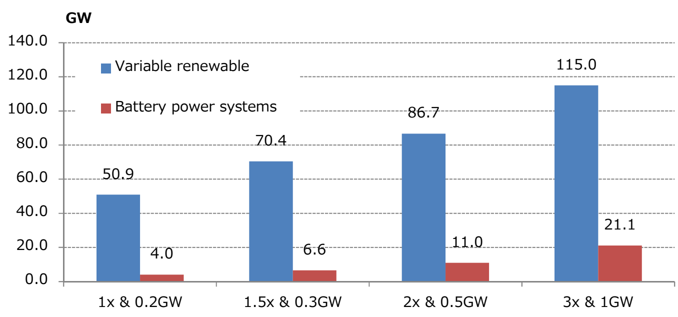


**Figure 3 - Introduction Amounts of Battery Power Systems and Variable Renewable Energy in the East Japan Area**

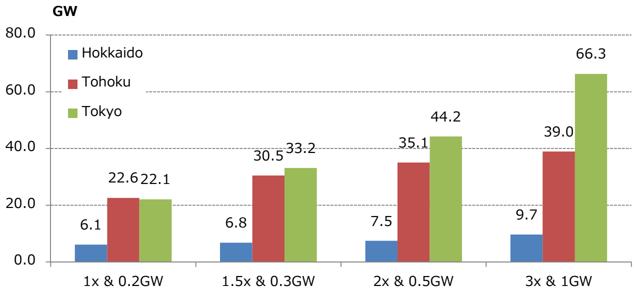


**Figure 4 - Introduction Amount of Variable Renewable Energy by Region in East Japan Area**

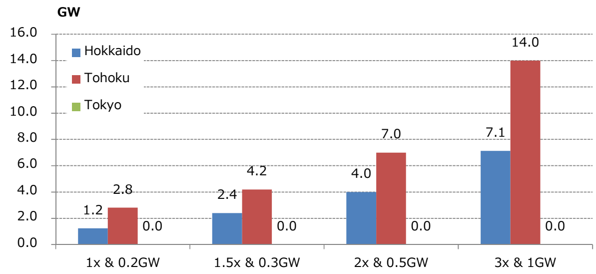


**Figure 5 - Introduction Amount of Battery Power Systems by Region in East Japan Area**

Similarly, **Figure 6** contains the installed capacity of variable renewable energy and the introduction amount of battery power systems in the West Japan Area, while **Figure 7** and **Figure 8** indicate the introduction amounts of variable renewable energy and battery power systems in each power company control area. The introduction of renewable energy is more widely distributed in the West Japan Area than in the East Japan Area and the grid mix also differs; as a result, the introduction amount of battery power systems will be less. When viewed by area, the introduction of variable renewable energy will advance to the upper limit in urban areas such as Chubu and Kansai, but in Shikoku and Kyushu, it has already peaked. The introduction amount of battery power systems will advance mainly in the Kyushu control area, but if variable renewable energy increases extremely, it will also increase in other areas.

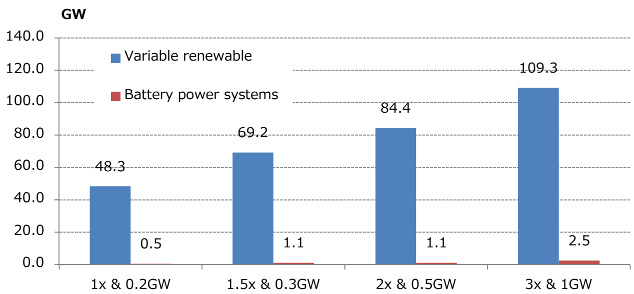


**Figure 6 - Introduction Amounts of Battery Power Systems and Variable Renewable Energy in West Japan Area**

Low-Carbon Society calls for "aim to achieve an emissions coefficient of around 0.37kg-C02/kWh (usage end) in fiscal 2030." [9)]

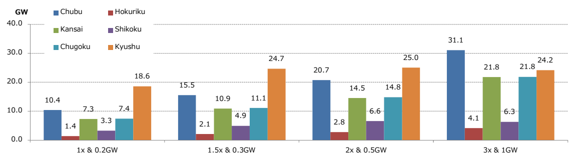


**Figure 7 - Introduction Amount of Variable Renewable Energy by Region in West Japan Area**

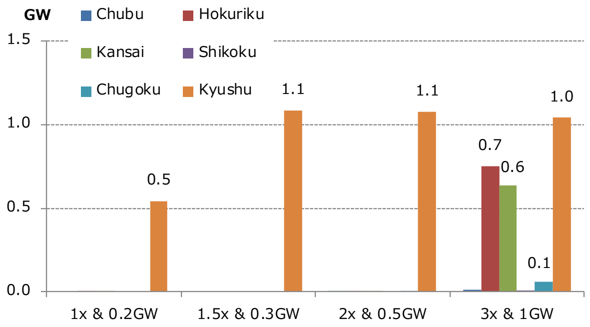


**Figure 8 - Introduction Amount of Battery Power Systems by Region in West Japan Area**

This analysis indicates that there is room for introducing variable renewable energy in Tokyo and Chubu Electric Power Company control areas with large electricity demand and control reserve capacity as pointed out by the Fujii-Komiyama Lab (2016) [2)]. In other words, there is a possibility of a link between increases in upper limit of capacity of renewables and growth in introduction amounts in the urban areas like Tokyo Electric Power Company. The problem of the uneven distribution of renewable energy overall in Japan, supply-demand balance issues, and control reserve issues, indicate there is gap between regions, and even when increasing the upper limit of installed capacity of variable renewable energy, this does not necessarily mean that the same amount of variable renewable energy will be introduced.

## 5. Discussion

This chapter will examine the policy implications taking into account the results of the analysis of the previous chapter.

### 5.1 Policy Implications

When considering the power generation mix of 2030 and beyond, approaches to facility mix must also be examined while keeping an eye on 2050 as well. For example, when including 2040 or 2050, FIT based on long-term purchases will need to be further revised by 2020. Based on the results of this analysis, we believe a policy response is warranted for the following points.

**(1) Rectifying Uneven Distribution of Renewable Energy Regionally and Resource Bias**

In this analysis, we referenced the quota for each power company control area assumed by OCCTO, including the regional bias based on the long-term outlook. The analysis results indicate advancing the introduction of renewable energy in a format of expanding the current situation will have an even greater impact on uneven distribution regionally in the future. Currently, renewable energy grid connections are being solicited, taking into account the available capacity of the grid, but over a more long-term outlook, considering the installation trends of thermal power and others, an examination of the regional balance of renewable energy will be needed. For this reason, consideration must be given to assigning purchase price differences based on region under FIT, which has a nationwide uniform purchase price, or making revisions so as to establish solicitation quotas for each area. In examinations of the further penetration and expansion of renewable energy, attention often focuses on photovoltaic power generation or wind power generation because of the potential and cost reduction possibilities, but such examinations must strike a balance in terms of the resources of renewable energy based on the bias of suitable locations and uneven distribution of power generation characteristics.

**(2) Curtailment and Securing of New Control Reserves**

Based on the results of this analysis, it was observed that the growth in the introduction of variable renewable energy curtailed nuclear power and controllable renewable energy. Given there has been a lack of negative control reserve margin, this requires measures for securing control reserves including on the demand side. Also, there are some regions where it is difficult to introduce additional variable renewable energy given control reserve constraints. Facilities that provide controls, such as stabilization of frequency and electrical voltage, will need to be more widely considered in the future, including not only thermal power, but also renewable energy and pumped storage, battery power systems and further on the demand side, given constraints of greenhouse gas reductions in the future. In addition, control reserves will need to be secured, taking into account the regional outlook for thermal power facilities, and the technical development needed for this must also be promoted as policy.

**(3) Utilization of Energy Storage Systems**

Based on the results of this analysis, the introduction of battery power systems is believed to be an effective measure for the penetration and expansion of variable renewable energy. In order to penetrate variable renewable energy as the mainstay of renewable energy in the future, the use of energy storage systems is expected, including storage batteries, hydrogen and heat. In doing so, these systems are expected to be utilized for securing a kWh basis balance and be capable of providing a function of grid stabilization including control reserves. Each system requires the necessary supply capability and control reserve based on orders of the grid operator. Furthermore, in this analysis, we assumed that battery power systems can be controlled from the grid, and another important issue is whether energy storage systems installed on the demand side can be utilized following the orders of the grid operator. Demonstration testing is being conducted on VPP, but examination is needed into the cross-regional usage potential of all energy storage technologies, including making them larger in scale.

**(4) Flexibility of Demand Side**

In this analysis, demand is not subject to optimization. However, the introduction of electric vehicles and utilization of demand response in the future is expected to require a response from the demand side in conjunction with the grid situation, including securing negative control reserve margin. In addition, there is the possibility that secession of demand following advancements in the creation of micro grids using diversified power sources and collaboration between small scale grids and the main grid will become issues.

### 5.2 Future Issues

In this analysis, demand, power generation patterns of renewable energy, power generation facility mix excluding variable renewable energy were given, and an analysis of power generation mix was carried by using linear programming model. The following points are issues for the future quantitative assessment by this model.

As for demand, assumptions of the level of future demand and examination of greater flexibility of demand will be needed. In terms of renewable energy, review of the outlook of regional bias, approaches to upper limit levels, estimates of introduction of renewable energy outside of variable renewable energy, and output fluctuations including forecasting errors will be issues. Japan’s electric network configuration including interconnections, how to look at development plans and battery power system assumptions as grid facilities and the handling of battery power systems owned by customers will also become issues. In addition, when including 2050 and beyond in the field of view, backcasting analysis for the 80% reduction in greenhouse gases analysis of situations where photovoltaic power, wind power, and nuclear power can provide a certain degree of negative control reserve and analysis of necessary technical developments, will be issues.

Reviews on each of the above elements are now progressing at universities, academic societies and companies. Although 2040 and 2050 are far in the future, facilities certified under FIT that begin operations in 2017 have a high likelihood of operating until 2037. While we must take note the possibility that current policy dictates the future facility mix, we must examine forward-thinking policies and measures instead of ad hoc measure.

## 6. Conclusion

In this analysis, we analyzed the power generation mix for 2030 and beyond, and in particular 2040, using a model for power generation mix considering control reserve. This analysis also revealed issues to examine with regard to the future facility mix. Through this analysis, it was revealed that simply increasing the upper limit of installed capacity of variable renewable energy would not necessarily lead to the same amount of variable renewable energy input into the system, due to the problem of uneven distribution of renewable energy, issues of supply-demand balance, and control reserve constraints. While there is anticipated room in the introduction of variable renewable energy in urban areas such as Tokyo Electric Power Company, there is a regional gap where there is little room in regions such as Hokkaido and Kyushu. The implementation of support measures such as FIT that can define future facility amounts must be examined not only as current connection issues, but also to some extent considering the characteristics of future power systems. With a long-term view, areas must be revealed in Japan where there is room to accept renewable energy in the efficient use of facilities and allocation, and measures and policies for promoting the introduction of low carbon power sources will need to be executed.

Taking into account the power generation mix for 2030 indicated in the Long-term Energy Supply and Demand Outlook, in order to aim to achieve the reduction target for greenhouse gases in 2050, the evolution of thermal power generation facilities, review of control reserves using renewable energy, and advancements in technologies for battery power systems and on the demand side are anticipated. The electricity business is an infrastructure industry with a long lifespan. In order to achieve a facility mix that can accept diversified power sources which continue to spread at a quick speed, the current policies of FIT impacting the long-term must be reviewed and policies with a focus on advancements in R&D and the penetration and implementation of new technologies in society must be examined.

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