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Scenario analysis on future electricity supply and demand in Japan

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ABSTRACT

Under continuing policies of CO_2 emissions reduction, it is crucial to consider scenarios for Japan to realize a safe and clean future electricity system. The development plans for nuclear power and renewable energy - particularly solar and wind power - are being reconsidered in light of the Fukushima nuclear accident. To contribute to this, in the present study, three electricity supply scenarios for 2030 are proposed according to different future nuclear power development policies, and the maximum penetration of renewable energy generation is pursued. On the other side of the equation, three electricity demand scenarios are also proposed considering potential energy saving measures. The purpose of the study is to demonstrate quantitatively the technological, economic and environmental impacts of different supply policy selections and demand assumptions on future electricity systems. The scenario analysis is conducted using an input–output hour-by-hour simulation model subject to constraints from technological, economic and environmental perspectives. The obtained installed capacity mix, power generation mix, CO_2 emissions, and generation cost of the scenarios were inter-compared and analyzed. The penetration of renewable energy generation in a future electricity system in Japan, as well as its relationship with nuclear power share was uncovered.

1. Introduction

Electricity supply in Japan is highly dependent on nuclear power, which provided 30% of their electricity demand in 2010 from a total of 54 nuclear power plants (NPP). Nuclear power was expected to reach 68 GW installed capacity and contribute 40% electricity generation by 2030 under the Strategic Energy Plan (SEP) released by the government in 2010 [1]. However, all of the nuclear power reactors in the Kanto and Tohoku areas stopped when they were hit by the magnitude 9 earthquake and subsequent tsunami on March 11, 2011. Subsequent coolant losses in the reactors and spent fuel ponds at the Fukushima Daiichi power plant led to hydrogen explosions, fuel rod meltdown, contamination of the local environment and evacuation of local residents. It is quite certain that at least four of the six nuclear reactors at Fukushima Daiichi will be closed permanently, and the remaining stopped reactors are unlikely to resume operation in the near future in light of public concern [2]. The Fukushima nuclear accident changed the electricity supply structure dramatically and immediately for the short term.

However, from a long term viewpoint, apart from the safety issues of nuclear power, Japan also faces a very serious energy security problem, pressure to reduce greenhouse gas emissions (GHG's) and penetration of renewable energy generation bottlenecks from technological, systemic and economic perspectives. Energy supply in Japan is 96% dependent on overseas imports [3], and the price of energy resources is still increasing in international markets [4]. The domestic CO_2 emissions in Japan have increased by 20% compared to 1990 levels in the electricity generation sector up to 2009 [5] despite commitments to emissions reductions. Therefore, building new coal-fired and oil-fired power plants seems to be an undesirable choice even in a situation of electricity shortage. On the other hand, the potential of renewable energy - mainly including photovoltaic (PV) and wind power - is limited in Japan due to physical-geographic reasons and constraints in technology and system integration [6]. Therefore it is crucial to reconsider the energy policy across the whole country in the mid-to-long term to realize a future clean and safe electricity system considering constraints from various perspectives.

Some previous studies have focused on the impact of the phase-out of nuclear power in the energy system in Japan [7,8], however penetration of renewable energy generation and subsequent excess electricity issues were not considered. The excess power issue with penetration of renewable energy generation has been studied particularly in Europe, however, excess power in those studies has been mainly due to a large proportion of combined heat and power (CHP) being used to supply heat and electricity simultaneously during cold weather [9,10]. Furthermore, there is good inter-connectivity in the European electricity grid which can buffer the effects of excess

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electricity production. In Japan, the situation is quite different, there is no inter-connection with other countries and excess power occurrences with high penetration of renewable energy are due to the electricity system being based on nuclear power with minimal load-following capability.

Although electricity demand has been studied in many countries [11–14] using various models [15], the demand is decided by many factors including technology efficiency improvement, socio-economic factors, disasters, etc. which bring with them high levels of uncertainty. Therefore, in the present study, the scenario analysis method is employed to study the demand-supply balance in future electricity systems. In the methodology, supply scenarios are generated based on physical data and policy selections; on the other hand, the demand scenarios are generated by assumptions attempting to determine whether the system could respond to these uncertainties. This study presents scenario analysis of the Japanese electricity system in 2030, in light of the Fukushima nuclear accident using a model which incorporates aspects of resource availability, technology, economy and environment. The study focuses on the electricity demand-supply balance, and all the scenarios are analyzed and compared on multiple performance indicators. Nuclear reactors considered in this study would be new generation technology that incorporates "passive" safety features intended to avoid disasters like the one in Fukushima. In the event of an accident, the reactor relies on natural forces such as gravity and condensation to help keep its nuclear fuel from dangerously overheating—features the Fukushima plant lacked. Furthermore, very high standard anti-earthquake (and tsunami) technologies will be employed in nuclear power plants in the future.

2. Scenario analysis methodology

2.1. Electricity supply-demand scenarios

In the scenario analysis on supply-demand in electricity system, installed capacities of nuclear power and thermal power are decided by their development strategy and their stipulated lifetime, and thus given as preconditions, which will be introduced in the following section in details. The purpose of the study is to propose electricity supply systems with maximum penetration of renewable energy generation subject to various defined rules, under different nuclear power development strategies and demand levels through scenario analysis.

As shown in Fig. 1, when electricity supply capacity is significantly above the demand level (S-1 in Area1, S-2 in Area1 and 2, S-3 in Area1, 2 and 3), there are a number of options for supply capacity mix or demand reduction. On the other hand, under-supply is not acceptable, leading to conditions where demand must be cut or installed capacity must be increased to realize an adequate supply-demand balance. Therefore, in this study, the scenario analysis is conducted based on both supply and demand sides. And the matches between different supply and demand options are discussed based on the obtained simulation results and the values of performance indicators.

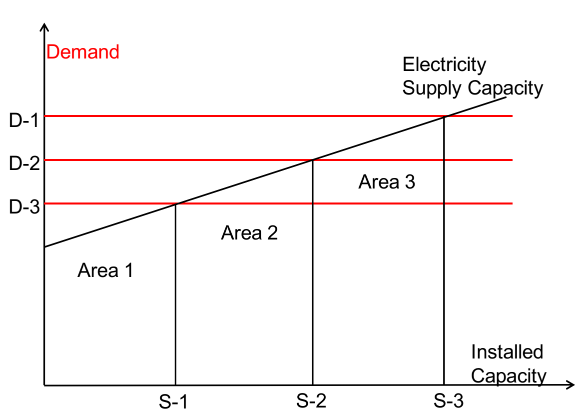

Fig. 1. Energy demand-supply scenario analysis.

In detail, the purpose of the comparative analysis on multiple electricity supply-demand scenarios in Japan in this study is to understand the following issues:

(1) the constraints of the penetration of renewable energy from the perspective system integration in terms of the occurrence of excess electricity;
(2) the role of nuclear power in the whole system and whether or not it can be removed;
(3) contribution of renewable energy in different scenarios;
(4) the impact of the penetration of renewable energy on average power generation cost;
(5) CO_2 emissions reduction compared to 1990 levels as representative of the environmental aspect.

2.2. Framework of the scenario analysis methodology

The scenario analysis methodology and main contents are shown in Fig. 2. It is organized in an "Input-Output" framework and actualized by hour-by-hour demand-supply balance computer simulation. The data and rules are generated by the "Scenario Generator". On the supply-side, the scenarios are based on physical data and policy selections, on the other hand, on the demand side, the scenarios are based on historical data and assumptions considering uncontrollable uncertainties. The arrows in the figure show the data flow direction. Main data inputs are demand, solar irradiation, wind speed, fuel supply, installed capacity, CO_2 emissions factor and basic cost information (for full list see tables in following sections). Main rules inputs are classed into technological, economic and environmental perspectives, with emphasis on prohibition of blackouts, generation priority of power sources, upper limitation of excess electricity, range of capacity factor, cost and CO_2 emission constraints respectively. All the defined rules will become constraints for the hour-by-hour simulation. Outputs are energy balances and resulting annual production, fuel consumption, total/average cost, total/average CO_2 emissions, etc. The explanations of the main "Data" and "Rules" will be given in details in Section 3 and Section 4 respectively.

Previously, many models have been proposed and developed for the energy (electricity) mix with penetration of renewable energy generation [16,17]. Some of them are based on hour-by-hour simulation [18,19]. However, the model used in the present study is unique in that it focuses on nuclear power based electricity systems to integrate renewable power in Japan, and the purpose of analysis is not only economic (investment) performance, but also CO_2 emissions and energy supply security are considered seriously. This study considers supply-side policies as the main component affecting the ability of the system to meet demand.

2.3. Simulation flow

The general simulation flow is shown in Fig. 3. Electricity generation from renewable and nuclear energy are considered as basic supply, when these exceed traditional electricity load, surplus electricity will be used to drive pumped hydropower plants. On the other hand, when basic electricity supply from renewable and nuclear energy is less than traditional load, battery and peak supply

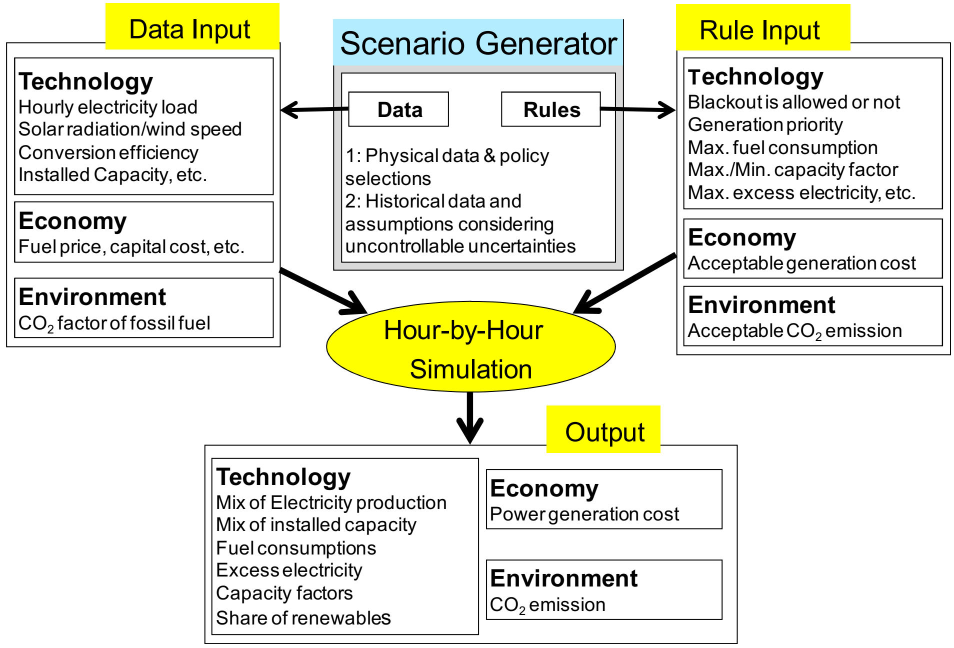

Fig. 2. Methodology for scenario analysis on electricity supply-demand.

(LNG, biomass, oil) and pumped hydropower try to meet the deficiency in electricity. Finally, if no blackout happens, the system is considered as technology feasible, otherwise initial data will be changed and new iteration will start. In the simulation flow, 1 h ahead forecast is assumed and peak supply is considered to have 100% output change capacity per hour. Therefore, peak supply and pumping hydropower have the ramping capacity to absorb fluctuations of renewable energy on the hourly basic.

3. Main input preconditions

3.1. *Electricity demand*

The hourly distribution of electricity demand in 2001 is shown in Fig. 4 [20]. The electricity production increased by about 30% in the last 20 years from 740 TWh in 1990 to 940 TWh in 2001, and 960 TWh in 2009 [20], but in the last 10 years, the demand has stayed almost level. However, on the demand side, energy saving is a key focus especially since the Fukushima accident (in recognition that the ability to install new capacity is limited) [2], and possible population reduction is also predicted. The demand is decided by many factors including the socio-economic situation, disasters and unforeseen technological development, and on the uncertainty around these factors is high. Therefore, in the present study, the demand scenarios are generated based on assumptions that incorporate these uncontrollable uncertainties. Therefore, we assume that demand remains at 2009 level in the first demand scenario (D1); 15% reduction is realized in the second demand scenario (D2); and a 30% reduction is realized in the third scenario (D3). As shown in Fig. 5 [21], industry, residential and commercial occupied about 30% each respectively in electricity consumption in Japan from 1990 to 2008. In D2, it may be possible to reduce 5% in all the three sectors respectively through lifestyle change, efficiency improvements etc. This level of reduction has been demonstrated in the wake of the March 11 earthquake [22], and may prospectively be maintained through cultural and technological changes. On the other hand, in D3, steeper reductions would be required. These reductions could come from a range of options, but some suggestions might be:

- a reduction of 10% of the total (30% of the sector) in each of the three sectors respectively
- or more drastic measures such as moving all heavy industry overseas (roughly 30% of the total)
- or steeper cuts in household and commercial consumption (50% each).

The achievement of the D3 cuts would be reliant on technological improvement or significant policy and economic shifts. Japanese use of electricity in the residential sector is mainly for appliances, hot water and space heating/cooling [23]– insulation and solar hot water heating might go some way to reducing electricity usage, but efficiency of appliances or reduction in their usage is the area of greatest potential. Japan's industrial sector is already among the most efficient globally, and would be expected to find it

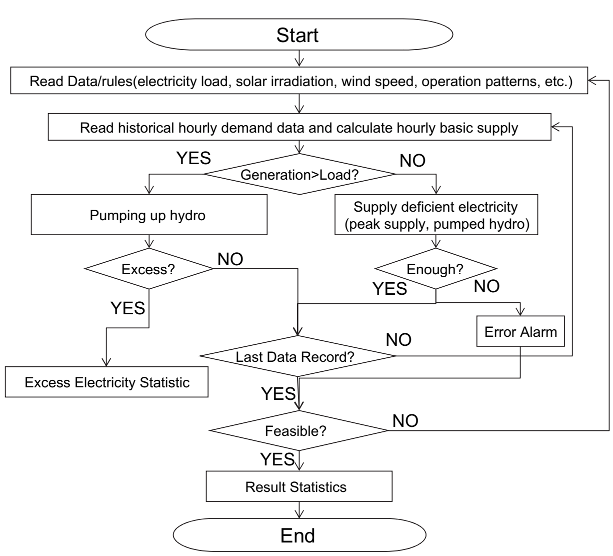

Fig. 3. Concept flow chart of the hour-by-hour simulation method.

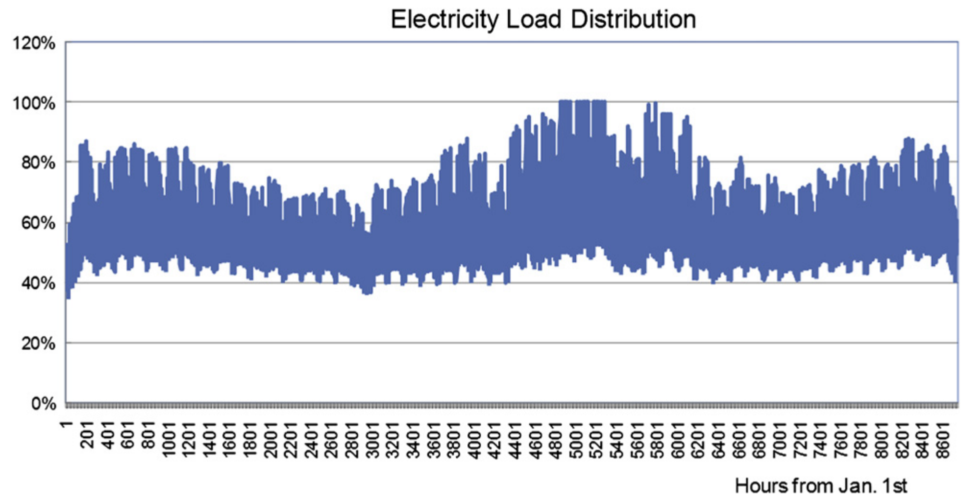

Fig. 4. Hourly distribution of electricity load.

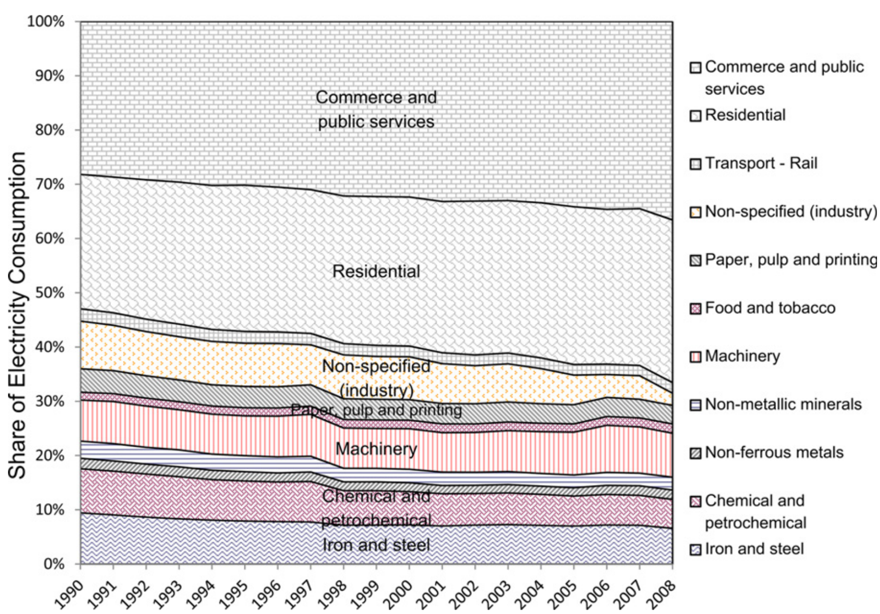

Fig. 5. Electricity consumption shares at demand side.

difficult to improve further without technological evolution. The variety of demand reduction strategies are not the key focus of this work however, meeting potential demand levels, and finding the lowest emissions mix under given supply-side policies is the main interest here – which is why the 3 levels of demand are used for the scenarios.

3.2. *Capacities of nuclear power and thermal power*

Three supply scenarios are proposed according to different nuclear power development strategies in light of the Fukushima nuclear accident: (1) negative nuclear power; (2) conservative nuclear power; and (3) active pursuit of nuclear power as shown in Fig. 6. In the negative nuclear scenario (N1), the NPPs stopped in the March 11 earthquake will be closed permanently, all NPPs under construction and in planning will be canceled and the NPPs in operation will be closed at the early end of their proposed lifetime range (35–40 years). On the other hand, in the conservative nuclear

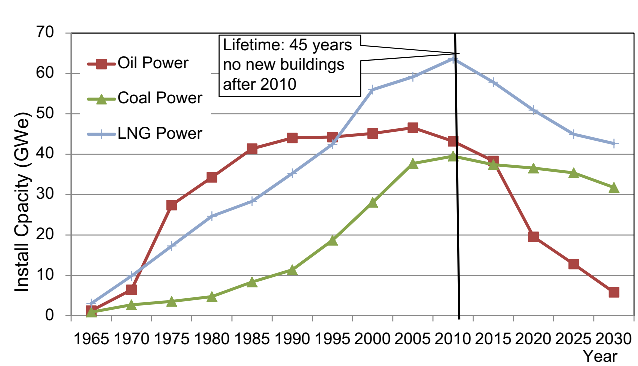

Fig. 6. Three scenarios of nuclear power development in Japan up till to 2030.

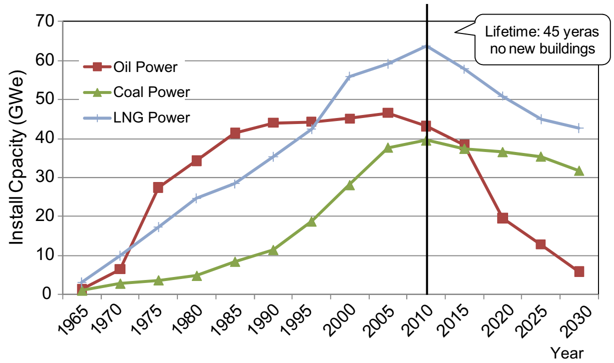

Fig. 7. Installed capacities of thermal power in Japan up till to 2030.

power (N2) and active pursuit of nuclear power (N3), all NPPs under construction and in planning will be continued according to the schedule and all NPPs will operate for a long lifetime 40–50 years and very long lifetime 50–60 years, respectively. Furthermore, in N3 Fukushima Daiichi NPPs will be rebuilt before 2030.

If all the thermal power plants (coal, LNG, oil) are stipulated to have 45 year lifetimes, and there will be no new construction of thermal plants up till 2030, the installed capacities of thermal power plants are shown in Fig. 7 based on historical installed capacity data [24]. This is the basic installed capacity for thermal power, and in the scenario analysis, new LNG power plants can be built when necessary to provide sufficient capacity.

Based on this, the installed capacities of nuclear power and thermal power in 2030 in the three proposed scenarios are shown in Table 1. In the table, biomass power is assumed to remain at 2 GW as it was in 2009 [20].

3.3. *Renewable energy potential and fossil fuel supply*

Japan will have to increase the amount of electricity provided by renewable sources substantially, especially “new” sources such as wind, solar, and biomass, because the country’s hydroelectric potential has already been largely exploited. At present, the installed capacity of hydropower is 21 GWe and pumped storage hydropower is 27 GWe [25]. We assume both values will remain constant. The potential of renewable energy in Japan is listed in the following table. Here, we do not consider the constraints from production, cost, policy and other aspects, because the purpose of this study is to integrate renewable energy as much as possible. Instead, we have listed the potential based on available space and known climatic limits as shown in Table 2.

3.4. *Hourly data of renewable energy*

It is very difficult for traditional electricity mix models to integrate renewable energy sources because of the intermittency of solar and wind energy. Intermittent sources of electricity are expected to have technical and economic limitations in reaching a high level of penetration. The hour-by-hour simulation model is therefore vital here to test the supply-demand balance of the electricity system [28–30].

Table 1
Installed capacities of nuclear power and thermal power in 2030 (GWe).

Scenarios	Nuclear	Coal	LNG	Oil	Biomass
S1	14.34	31.8	42.6	5.8	2
S2	50.35	31.8	42.6	5.8	2
S3	60.75	31.8	42.6	5.8	2

Table 2
Renewable energy and hydropower potential [6,26,27].

Renewables	Potential
PV	100 GWp
Wind	50 GWp
Biomass	2 GWe
Hydro	21 GWe
Pumped Hydro	27 GWe

The output distribution of PV, wind power and their combination (installed capacity ratio 2:1) is shown in Fig. 8, and excess power for various levels of PV and wind penetration is shown in Fig. 9. Here, the solar irradiation and wind speed historical data in 2001 provided by JMA (Japan Meteorological Agency) is used [31]. For the purpose of this study, we did not incorporate the geographical dispersion of PV power and wind power, but rather used a national average to approximate the potential [32]. The data for Osaka are used to represent the whole country in this study, due to its location around the centre of the country’s climatic zones. In the figures, the “net power” means the difference between the normal load and the output of PV and wind power. The more PV and wind penetration in the system, the less net power will be and the more excess power will appear when the base load power source level is stipulated.

3.5. *Cost information*

The basic cost information for various power generation technologies is shown in Table 3. Furthermore, management and operation (MO) cost is assumed as 5% of the capital cost. For nuclear power, fuel recycle costs of about 1.5 yen/kWh also need to be considered. However, the future price of energy resources in the global market is quite uncertain (although likely to rise), and the given cost information is used as an example.

3.6. *CO_2 emission factor*

The CO_2 emissions factors of various power generation technologies are shown in Fig. 10 [36]. According to the calculations, in 2030, most coal-fired power plants will be advanced supercritical technology with 600 °C steam temperature, and LNG-fired power plants will be combined cycle plants (rather than open cycle) in Japan. CO_2 emissions could be reduced by about 5% and 20% respectively due to the efficiency improvements in advanced coal-fired and LNG-fired power generation technologies.

4. Main defined rules

The main defined rules for the hour-by-hour simulation are shown in Table 4, and the detailed explanations follow.

4.1. *Installed capacity, supply-demand balance and excess electricity*

The installed capacities of nuclear power and thermal power are decided by the development policy and the stipulated lifetime of existing plants. The purpose of the scenario is to integrate renewable energy as much as possible. When renewable energy is integrated into the electricity system as much as possible, if the supply is still not sufficient, new LNG power plants can be built. However, when penetration of renewable energy generation is still less than its potential, but much excess power occurs, firstly the capacity factor of coal-fired power will be lowered; however, when the capacity factor of coal-fired power is lowered to be zero, if excess

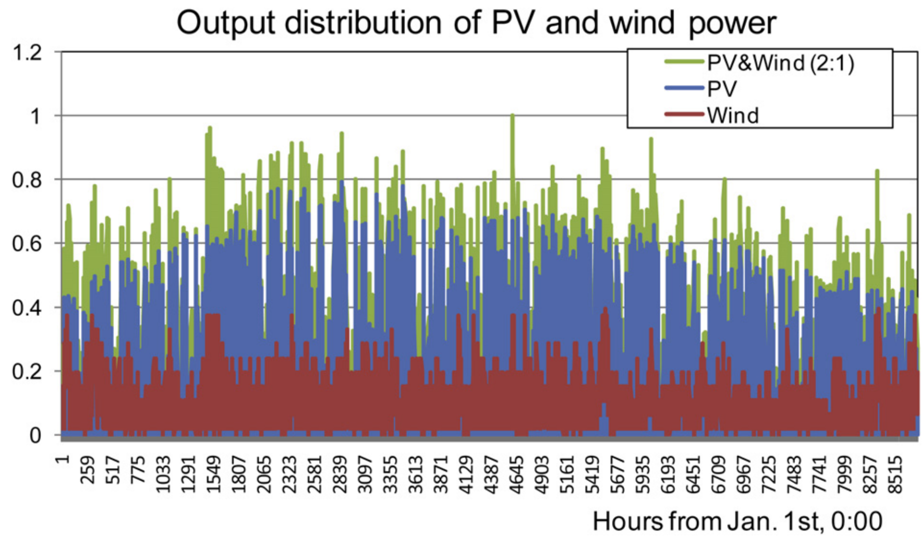

Fig. 8. Output fluctuation of PV, wind power and their combination.

power is still over its upper limitation, the further penetration of renewable power will be not allowed.

In order to evaluate the performance and reliability of the obtained optimized electricity mix, two parameters are employed. One is the deficiency of power supply probability (DPSP), the other is the relative excess power ratio (REPR). DPSP is used to evaluate the possibility of a deficiency in the power supply which can be calculated as shown in eq. (1), and the REPR is given as a ratio of the total annual excess power generated by the system, as expressed in Eq. (1). Here the TEL is the annual total electrical load; The Output and Load are the hourly electrical production and load respectively.

$$\text{DPSP} = \frac{\text{DPS}}{\text{TEL}} = \frac{\sum_{i=1}^{8760}(\text{Load}_i - (\text{Output}_i + \text{StorElectricity}_i))}{\sum_{i=1}^{8760}\text{Load}_i} \tag{1}$$

$$\text{REPR} = \frac{\text{REP}}{\text{TEL}} = \frac{\sum_{i=1}^{8760}(\text{Output}_i - (\text{Load}_i + \text{Storage}_i))}{\sum_{i=1}^{8760}\text{Load}_i} \tag{2}$$

In the present study, blackouts are not permitted; therefore, the DPSP must be zero at all times. Electricity generated by solar and wind is used as much as possible in the study, however, when excess power happens, it is difficult to lower the output of nuclear power as base load, so PV panels and wind turbines are controlled to lower their outputs in this situation, thus, any excess electricity is generated by PV and wind power. In the study, the maximum excess electricity ratios in the total generation and PV and wind generation are defined. Furthermore, of the carbon-based fuels, only new construction of LNG power plants is permitted due to the good performance in CO_2 emissions reduction and the absorption of intermittent electricity as a flexible power source.

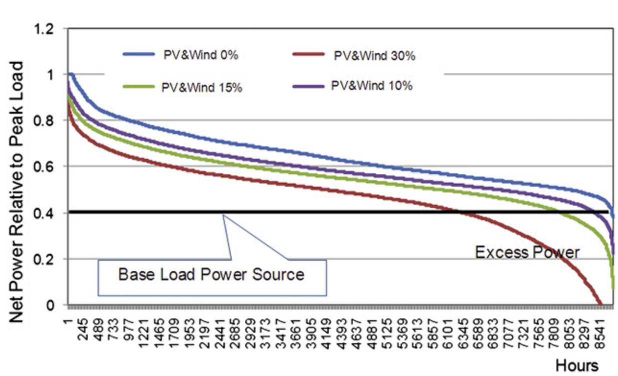

Fig. 9. Excess power in modified load duration curves for various levels of PV and wind penetration.

4.2. Power generation and electricity storage strategy

Hydropower, nuclear power and coal power are used to supply base load, gas for middle load and oil and pumped storage hydropower are used for peak load. If the pumped hydropower has more than half of its storage capacity, only surplus base load power, PV and wind power are stored, however, when its capacity becomes less than one third, gas power is operated specifically to increase the level of storage to ensure capacity. With the penetration of PV and wind power, if too much excess power is being produced annual capacity factor of coal power plants can be lowered even to zero.

4.3. Resource availability

Penetration of renewable energy generation must be less than physical potential of renewable energy sources, and the fossil fuel demand must be less than overseas import capacity. Power generation facilities such as PV panels and wind turbines can be made domestically in Japan, but can also be supplied from overseas. For example, 100 GWp PV power can be reached by installing 5 GWp per year from 2010 to 2030. Today approximately 2.5 GWp PV power can be produced in Japan [37], however the global

Table 3
Cost information of power generation technologies in 2030 [33,34,35].

	Capital cost (1000 yen/kW)	Discount	Lifetime (years)	Fuel cost (yen/MJ)
Nuclear	300	3%	50	0.18
Coal	272	3%	45	0.35
LNG	164	3%	45	0.57
Oil	269	3%	45	0.91
Biomass	500	3%	45	0.57
PV	200	3%	20	0
Wind	200	3%	20	0
Hydro	732	3%	60	0
Pumped Hydro	200	3%	60	0

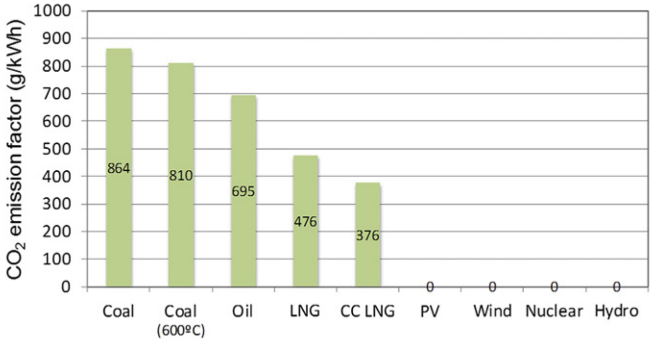

Fig. 10. CO_2 emissions factors of various power generation technologies.

production capacity is 15GWp [38]. Furthermore, the production capacities both domestically and in the world are expected to increase quickly in the future.

4.4. Capacity factor and load-following

Hydropower operates with 45% capacity factor to supply base load. The capacity factor of nuclear power is stipulated to be about 90% on average but has different monthly values from 75% to 100% depending on periodic inspection and maintenance. Coal-fired power also works as base load follow the nuclear power, however its maximum capacity factor is 85% and its annual average capacity factor can be lowered even to zero in order to integrate more renewable energy. The base load power supply cannot change its outputs very quickly, and thus does not operate in load-following mode. Gas, oil and hydropower can change their outputs by 100% within one h, and therefore can operate in load-following mode.

Table 4
Summary of main defined rules.

	Defined rules
Supply-demand	1. Blackouts are not allowed 2. Only PV and wind power can be sources of excess power 3. Excess power ratio must be less than 5% of total electricity and 30% of combined PV and wind power 4. New LNG power plants are allowed 5. New coal and oil power plants are not allowed
Power generation and storage	1. Generation priority sequence: hydro, Nuclear, coal, PV & Wind, LNG, biomass, oil, pumped hydro 2. Capacity factor of coal-fired power can be lowered to zero for more penetration of renewable energy generation 3. LNG power is used to drive pumped hydro as electricity storage during the night in case of peak demand periods
Resource Availability	1. Penetration of renewable energy generation must be less than its physical potential 2. Fossil fuel demand must be less than Max. supply capability 3. Power generation facilities can be imported from overseas
Capacity factor and load-following	1. Capacity factor of Nuclear is between 75% and 100%, coal power less than 85% 2. LNG power, oil power, pumped hydropower operates in load-following mode
Generation cost and CO_2 emission	1. Average annual power generation cost cannot exceed upper limitation (10 yen/kWh) 2. Average annual CO_2 emission per kWh cannot exceed 1990 level

The outputs of PV and wind are determined by solar radiation and wind speed respectively, and change continuously every hour.

4.5. CO_2 emissions reduction and cost constraints

In 1990, CO_2 emissions in Japan were 392 g/kWh per unit electricity generation and 290 Million tonnes in total. The CO_2 emission levels in 1990 will be used as a standard to evaluate the reduction in the electricity system scenarios. In the Strategic Energy Plan (SEP) 2030 released by the government in 2010, total CO_2 emissions reduction is expected to be 15% of 1990 levels. On the other hand, the average generation cost per unit electricity is an economic parameter which is regulated to avoid the scenario becoming too expensive. At present, renewable energy is much more expensive than traditional electricity; however its cost is expected to be reduced greatly to the competitive level of present traditional electricity [33]. Although there are many uncertainties in the prices of fossil fuels in future global markets and economic performance improvements of renewable energy, a maximum average power generation cost of 10 yen/kWh is used here to constrain the scenarios.

5. Scenario analysis results and discussion

5.1. Scenario design

As shown in Fig. 11, the maximum penetration of renewable energy generation scenarios in 2030 are obtained based on the three supply scenarios (S1, S2, and S3) and three demand scenarios (D1, D2 and D3) subject to various input preconditions and defined rules introduced above. The results will be shown and discussed from technological, economic and environmental perspectives.

5.2. Result in technological perspective

The obtained results of installed capacity mix, electricity mix and key performance indicators are shown in Fig. 12, Fig. 13 and Table 5. The results show that:

(1) In S1 with only 14.3 GWe nuclear power, even though a high level penetration of renewable energy is realized, a maximum of about 40 GWe new LNG power plants need to be built by 2030, and maximum about 40% more LNG needs to be imported from overseas in 2030 comparing with 2009 levels. Furthermore, coal-fired power has to operate at a high capacity factor of about 75% in S1.
(2) In S2 and S3 with 50.3 GWe and 60.7 GWe nuclear power respectively, no new LNG power plants need to be built, and at least 20% LNG fuel is saved in 2030 compared to 2009 levels. Coal-fired power can be removed from the electricity system absolutely with the help of renewable energy and energy saving in S2 and S3 to reduce CO_2 emissions.

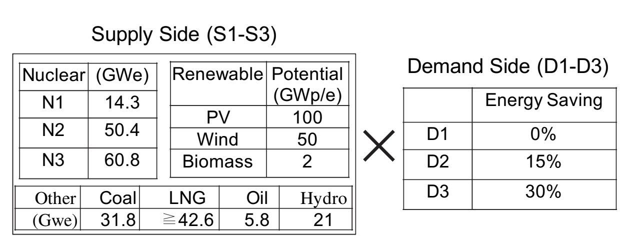

Fig. 11. Scenario design of electricity supply-demand scenarios in 2030.

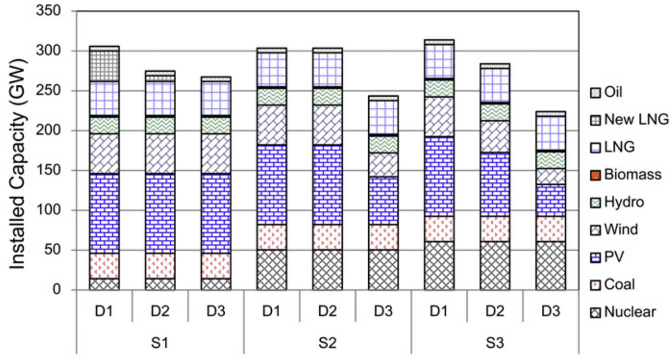

Fig. 12. Installed capacity mix of the supply-demand scenarios.

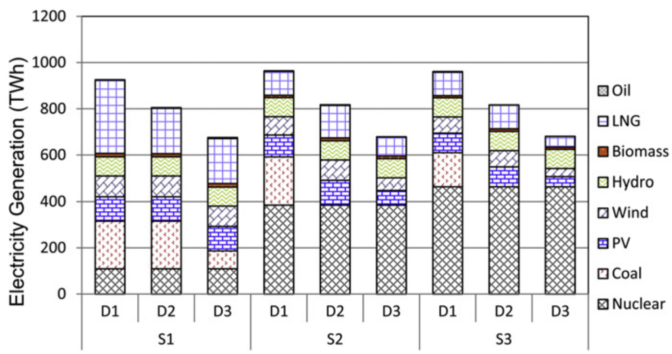

Fig. 13. Electricity generation of the supply-demand scenarios.

(3) Comparing S1 with S2 and S3 introduced in (1) and (2), we can understand that it is very difficult to remove nuclear power absolutely in an available, clean and safe future electricity system in Japan even if renewable energy penetrates as much as possible and energy saving is realized.

(4) In S2 and S3, the penetration level of renewable energy reduces from D1 to D3 with the demand reduction, because it is hindered by the increasing share of nuclear power as base load supply. It is shown that when power generation capacity become big enough relative to the demand, energy saving is optional and it is difficult for new renewable energy to penetrate into the whole system. Furthermore, there will be more excess electricity even when the capacity factor of coal-fired power is lowered to zero.

(5) Penetration of renewable energy can reduce the dependence on nuclear power and thermal power, but it needs flexible power sources such as LNG power to compensate for supply variability.

5.3. Result in economic perspective

The average power generation cost shown in Fig. 14, it is affected by many factors. Share of expensive renewable energy and excess power ratio lead to cost increases however, share of nuclear power and capacity factor of coal-fired power reduce costs. For example, the average cost of power generation in D3S1 is higher than in D2S1 and D1S1 because of the higher renewable energy share, higher excess power ratio and lower capacity factor of coal-fired power. However, in D3S1 the cost is higher than D3S2 and D3S3 because of more renewable share and less nuclear power share. None of the scenarios exceeded the upper limitation of 10 yen/kWh. However, power generation cost is highly dependent on the successful realization of PV power cost reduction, fossil fuel price in the global market and external impacts on nuclear power among other uncertainties.

Table 5
Analysis results of key performance parameters.

	Excess electricity share			Renewable share			Capacity factor of coal-fired power		
	S1	S2	S3	S1	S2	S3	S1	S2	S3
D1	0.9%	4.9%	4.5%	20.9%	18.1%	16.1%	74.1%	74.1%	52.3%
D2	2.7%	4.2%	4.2%	24.0%	23.7%	19.0%	74.1%	0%	0%
D3	3.5%	3.9%	4.3%	28.6%	17.1%	11.4%	27.9%	0%	0%

5.4. Result in environmental perspective

CO_2 emissions information is shown in Fig. 15. The CO_2 emissions per unit electricity are also affected by many factors. Higher shares of renewable energy and nuclear power and lower shares of thermal power can improve CO_2 emissions reduction. In the three

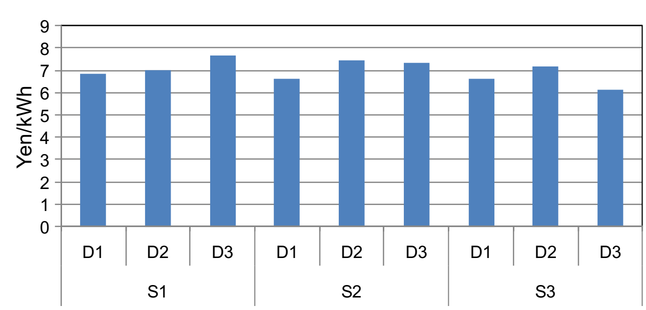

Fig. 14. Electricity generation cost of the supply-demand scenarios.

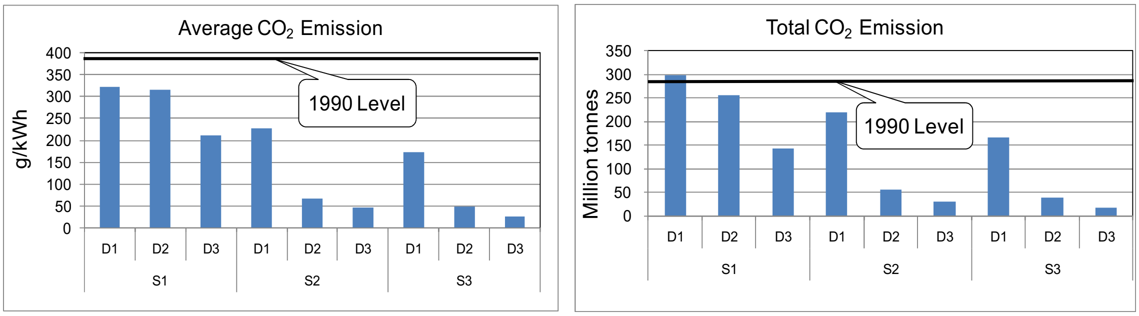

Fig. 15. CO_2 emission in the electricity supply-demand scenarios.

demand scenarios, the first supply scenario-S1 has much higher CO_2 emissions per unit electricity compared with S2 and S3 although the renewable energy share in S1 is higher, because more thermal power (mainly LNG) is introduced in the electricity system to compensate for energy shortages and to absorb fluctuations of renewable energy. However, compared to 1990 levels, the scenarios can all achieve an emissions reduction with the help of nuclear power, renewable power and energy saving.

5.5. Implications and discussions

If the "negative nuclear power" scenario is selected, even if renewable is developed as much as physically possible, Japan will have to face unstable fossil fuel availability in global market, CO_2 emissions/climate change pressures and possibly slow economic development due to electricity shortages. On the other hand, if the country is still dependent on nuclear power as in S3, the people and country have to face potential dangers of nuclear power, even if the most advanced technology is used. The authors provide several scenarios, of which D2S2 seems to be most practical and performs well from technological, economic and environmental perspectives. However, the scenarios - especially the nuclear development policy - will ultimately be self-selected by the people, government and industry of Japan.

In some situations, some individual locations use their own distributed renewable energy systems which are isolated from the larger grid system, and the management of these mini or micro grids will be through state-of-the-art HEMS (Home Energy Management System) and BEMS (Building Energy management System) [39,40]. In turn, these micro grids, and their interaction with the main grid system may be controlled and monitored by a central management system by power companies using SCADA (Supervisory Control and Data Acquisition) [41]. A number of authors have examined specific control equipment and control strategies which are of particular relevance to grid integration of distributed renewable energy. Furthermore, the challenges and control strategies for individual HEMS/BEMS are also the subject of ongoing work. It is apparent that there is a need for further development of technology to achieve the required quality of control. However, for the purpose of this study, we assume that all the renewable energy in individual locations are integrated into the larger grid system and that the electric power company can monitor and manage all of them using devices such as smart meters, SCADA. In the present study, the proposed methodology, is focusing on future electricity systems at the regional/national level, and we assumed that smart controls are realized automatically in individual locations in the target region/nation. In further studies, electricity supply-demand will be studied in different regions and the inter-connection between different regions will be the focus. Electricity storage using batteries and smart grid technologies with more new controllable loads such as electric vehicles and heap pumps will also be integrated into the modeled future electricity system.

6. Conclusions

This study focused on the balance and match of supply-demand in the future electricity system in Japan based on different supply policy selections and demand assumptions. Scenario analysis on the electricity system was conducted from technological, economic, and environmental perspectives using an input–output hour-by-hour simulation model. The results of the analyses demonstrate quantitatively the technological, economic and environmental impacts of different supply policy selections and demand assumptions.

The obtained results show that:

(1) penetration level of renewable energy is subject to the share of nuclear power as base load due to the occurrence of excess electricity, for example, renewable energy share is lowered from 20% in D2S3 to 10% in D3S3;
(2) It is very difficult to remove nuclear power absolutely from the electricity system even though high level penetration of renewable energy is realized, because the renewable energy contributes maximum of about 30% in D3S1 with maximum energy saving and maximum penetration of renewable energy generation;
(3) renewable energy contributes 10–30% in each of the scenarios, and the high level of penetration of renewable energy generation can reduce the dependence on nuclear and thermal power, but needs more flexible power sources to absorb fluctuations;
(4) high penetration of renewable energy generation will increase cost due to its relative high cost and associated lowering of the capacity factor of thermal power plants, for example cost is increased from 7yen/kWh in D1S1 to 8 yen/kWh in D3S1;
(5) CO_2 emissions reduction compared to 1990 level can be realized readily with the help of nuclear power, renewable energy and energy saving by 2030. Except S1D1, in other scenarios, CO_2 emissions are from 10 million tonnes to 250 million tonnes comparing with 290 million tonnes in 1990.

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