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Analysis of optimal locations for power stations and their impact on industrial symbiosis planning under transition toward low-carbon power sector in Japan

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ABSTRACT

Power plants are one of key energy sources for industrial symbiosis complexes. However, decarbonization of the power sector, including decommissioning of existing fossil-fuel power plants, aggregation of power plant sites, and capacity augmentation of carbon-free power plants, is necessary to achieve low-carbon societies in the long term. Decarbonization results in declining advantage for industrial symbiosis complexes that rely on fossil-fuel power plants. To establish sustainable industrial symbiosis complexes, we used a quantitative model to analyze optimal locations and scales for power plants in Japan considering CO_2 emissions reduction targets and several demand scenarios. Our results showed that even with a target of 80% CO_2 emission reduction, almost half of Japan's electricity generation could come from fossil-fuel power plants in 2050 if CCS technology were deployed widely. Fossil-fuel power plants would be developed mainly in the regions of high electricity demand and little wind power potential, such as Tokyo, Chubu, and Kansai. From an intra-regional perspective, fossil-fuel power plants could be constructed in areas of high electricity demand. In addition, except for the above areas, generation from fossil-fuel power plants would vary in accordance with the availability of renewables and electricity demand. Our results indicate that future climate policy, regional electricity demand, and availability of regional renewables should be considered when planning the development of industrial symbiosis complexes.

1. Introduction

Industrial symbiosis is one of the key concepts for using energy and resources effectively, and for reducing greenhouse gas emissions. Chertow (2000) defined industrial symbiosis as engaging “traditionally separate industries in a collective approach to competitive advantage involving physical exchanges of materials, energy, water, and/or by-products.” The energy carried by waste heat from fossil-fuel power plants is supplied to other industries in an industrial symbiosis complex, in addition to waste heat from energy-intensive industries such as the steel. The industrial symbiosis complex in Kalundborg, Denmark, distributes waste heat from coal-fired power plants to residents for heating, and to other industries (Jacobsen, 2006; Ohnishi et al., 2014). In Guayama, Puerto Rico, steam from a coal-fired power plant is provided to an oil refinery (Chertow and Lombardi, 2005). Some studies have discussed the feasibility of using waste heat from power plants and have showed large energy potentials for each analytical area (CASE, 2009; Bowman, 2012). In Japan, although industrial symbiosis complex–related policy has focused mainly on effective material use, there is increasing expectation to use waste heat from power plants. In the Eco-Town of Kawasaki, Japan, waste heat from natural gas combined-cycle power plants is distributed to industrial plants in the surrounding areas (Ohnishi et al., 2014). This practice has reduced energy demand and CO2 emissions by 283.8 GJ and 25 kt, respectively, compared to the use of only conventional energy systems. The development of industrial symbiosis complexes using waste heat from power plants in Shinchi, a town in Fukushima prefecture, is under consideration (Togawa et al., 2014).

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However, decarbonization of the power sector is necessary to achieve a low-carbon society in the long term. Actions to this end include decommissioning existing fossil-fuel power plants, aggregating power plant sites, and enhancing low-carbon and carbon-free power plants such as fossil-fuel power plants with CO2 capture and storage (CCS) technologies and renewable energy–based plants. Energy Technology Perspectives 2014 conducted by International Energy Agency introduced the 2 °C Scenario (2DS), which describes actions toward building a sustainable energy system to reduce greenhouse gas emissions. According to 2DS, renewable energy would become the dominant electricity source, accounting for 65% of global electric power generation in 2050, while fossil-fuel power plants would cover 20%. The AIM modeling team (2010) suggested a future generation mix for Japan that could achieve 80% reduction in CO_2 emission by 2050 compared to 1990 levels. According to this analysis, electricity generation from fossil-fuel power plants, which contributed 60% of total generation in 2010, would contribute only 20% of total generation in 2050. This implies that only 30 fossil-fuel power plants would be operated at a capacity factor of 80% and average capacity per generator of 1 GW. To establish sustainable industrial symbiosis complexes in a low-carbon scenario, it is necessary to identify locations near power plants that may operate until 2050, even under the emissions reduction targets, or to set up power plants near the locations of future industrial symbiosis complexes. Because, in general, new fossil-fuel power plants will replace decommissioned plants on existing sites, the possibility of the former case is higher. Thus, it is important to identify the locations, scales, and types of power plants under transition toward a low-carbon power sector.

The purpose of this study is to analyze the optimal location and scale of power plants for reducing fossil carbon consumption in Japan's power sector and to assess the effects of those locations and scales on industrial symbiosis planning based on quantitative evaluation using a model developed to consider regional power demand distribution.

To analyze the optimal locations and scales of power plants, we first developed a model which can consider the regionality of power systems in Japan. Next, we set 16 cases which incorporate uncertainties in the future electricity demand, the CO_2 emission reduction targets, and the development of renewables. We then simulated future electricity systems under these cases using the developed model. Finally, we analyzed the optimal locations and scales of power plants from the simulation results.

2. Current status in Japan

2.1. Status of Japanese power sector

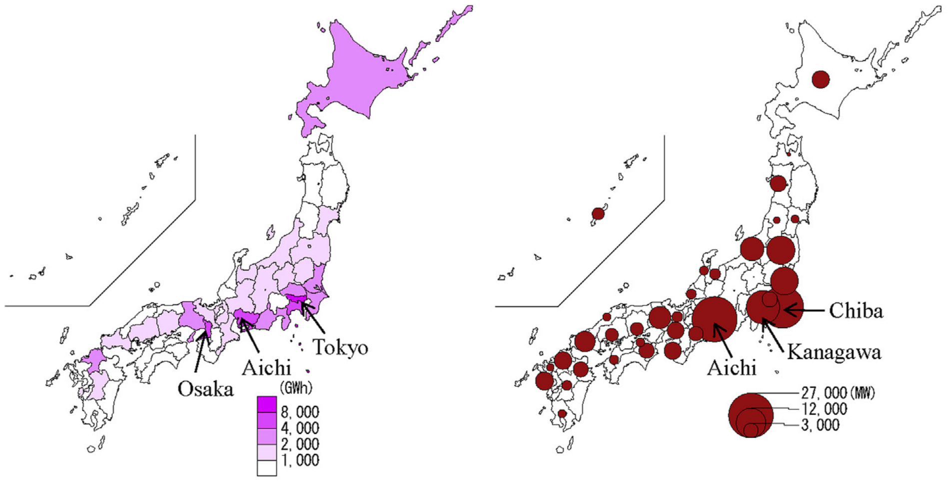
Electricity demand in Japan has been increasing gradually along with economic and population growth, and it almost saturated at around 900 TWh after 2005. As of 2015, 10 major electric companies handle generation, transmission, and distribution of electricity in Japan. Although interregional transmission lines connect the grids of these companies, cooperation among the companies is weak because the capacities of the interregional transmission lines are inadequate. Considering the above situation, Japanese electricity grids are divided into 10 regions based on general electricity utilities, namely, Hokkaido, Tohoku, Tokyo, Chubu, Hokuriku, Kansai, Chugoku, Shikoku, Kyushu, and Okinawa.

Electricity demand by prefecture in 2010 is shown in Fig. 1(a) (METI, 2011a). Japanese electricity demand is concentrated along the Pacific Coast and the Seto Inland Sea, with the metropolitan areas of Tokyo, Osaka, and Aichi prefectures being the major consumers. Electricity demand in the southern Kanto area, which includes Tokyo, Chiba, Kanagawa, and Saitama, is huge and accounts for about 25% of Japan's electricity demand.

Fig. 1 (b) shows the existing capacities of fossil-fuel power plants in Japan (METI, 2011b). These plants are located in coastal prefectures because almost all of the fuel for fossil-fuel power plants is imported into Japan by sea, and Japanese fossil-fuel power plants use seawater for cooling. Moreover, prefectures with high electricity demand, such as Aichi, Chiba, and Kanagawa, have large fossil-fuel-based power generation capacities.

2.2. Existing industrial symbiosis complexes

Industrial symbiosis complexes in Japan are associated with the Eco-town program (Ohnishi et al., 2014). The Eco-town program was initiated in 1997 and was designed to promote advanced city planning in accordance with the zero-emission concept. This concept aims for zero waste from any industry through the exchange of waste among industries, and it is a basic concept for regional development. Because the Eco-town policy focused on material recycling, there are many Eco-towns with plastic and electrical appliance recycling facilities, but only two Eco-towns feature energy exchange (MOE, 2014): Kawasaki Eco-town, which uses waste heat from a natural gas combined cycle power plant,



(a) Regional electricity demand (b) Existing capacity of fossil-fuel power plants

Fig. 1. Status of Japanese power sector in 2010.

and Kitakyushu Eco-town, which uses waste heat from industrial plants to power a heat supply system. However, energy exchange is becoming more desirable in the face of rising pressure for increasing energy efficiency and reducing greenhouse gas emissions. For example, the use of waste heat from a fossil-fuel power plant in Shinchi town, Fukushima prefecture, has been discussed (Togawa et al., 2014). Two coal-fired power plants are located there, and there are plans to construct liquefied natural gas (LNG) bases. In addition, redevelopment of the city center and policies to attract industry are under consideration to rebuild the city, which suffered considerable damage in the earthquake of March 11, 2011. Togawa et al. (2014) assessed the feasibility of energy symbiosis in this town via quantitative analysis considering the construction costs of heat pipelines and the heat lost in distribution. The Eco-town location and the planned industrial symbiosis complex are shown in Fig. 2.

3. Determinants of power plant siting

What is the determinant of fossil-fuel power plant location? Several studies have focused on fossil-fuel power plant location, although some of them are from the 1970s–1980s, a period characterized by a rapid increase in fossil-fuel power generation capacity.

Calzonetti et al. (1980) focused on coal power plant siting in the Rocky Mountains and Northern Great Plains states in the United States. They mentioned that some states used “site screening analysis” to search for coal power plant sites. By using this analysis method, firms concerned with engineering and economic criteria can act in conjunction with government agencies to minimize land-use conflict. In addition, Calzonetti et al. reported a “one-stop siting” system, which regulates firms to consider various categories of permits and reviews with the following ones being mandatory: water, air, health, wildlife, economic and community development, state parks, and historic sites.

Garrone and Groppi (2012) explored the siting decisions of Italian power producers and offered the determinants of thermal power plant location after liberalization in 1990. They assumed that location choices are determined by province characteristics, namely, infrastructure availability, profitability, environmental costs, community awareness and willingness to accept, and the voice potential of residents and estimated the expectation and strength of each characteristic to determine authorization applications. They concluded that infrastructure availability and the voice potential of residents were critical factors in the siting decisions of power producers.

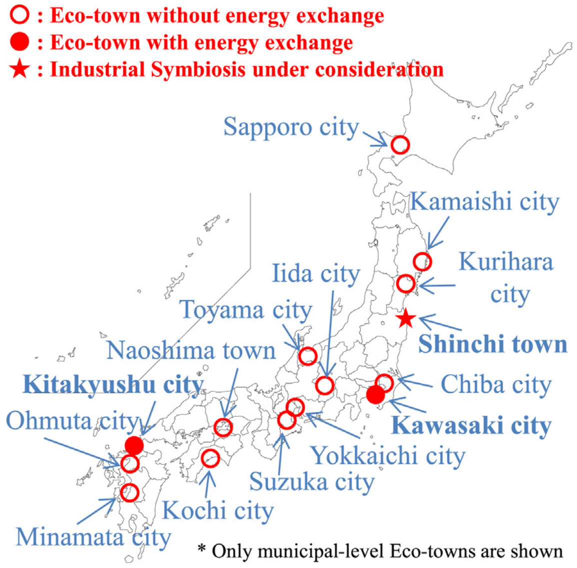


Fig. 2. Eco-town locations and industrial symbiosis complexes under consideration.

Amano (1974) presented a location selection method for power plants in Japan. This method selects power plant location through a four-step screening process. The first screen removes “absolutely unsuitable sites” such as sites prohibited by law or sites designated as nature conservation areas. The second screen considers the “relative value” of an area, such as its expanse, availability of industrial water, and level of air/water pollution in the surrounding area. The third screen is based on “economic aspects” such as cost of industrial water, transmission costs, and distance from fuel-receiving terminals. The fourth screen considers “social acceptability of residents.” Especially for the fourth (social) screen, Aldrich (2008) focused on siting problems in nuclear power plant development in Japan and pointed out how utilities and the government overcome opposition from local and external anti-nuclear groups.

Based on the existing studies, we can classify the determinants of “new power plant” siting into three factor groups: social (e.g., social acceptability, community development), regulatory (e.g., environmental protection, land-use restriction, historic site protection), and economic (e.g., infrastructure availability, profitability). However, under the greenhouse gas emissions reduction targets, such as 2° target, overall fossil-fuel power plant capacity will decrease and new fossil-fuel power plants will replace decommissioned plants on the existing sites. In fact, 82% of the fossil-fuel power plants constructed between FY2003 and FY2014 in Japan were built on existing sites (METI, 2011b). Under such “replacement” conditions, the economic factor is the most prominent factor in location selection because existing sites would have already passed the social and regulatory screens. Thus, it is appropriate to develop a model that can estimate future fossil-fuel power plant locations by optimizing economic factors. In addition, social and regulatory factors are also key determinants of power plant siting. These factors change dynamically and can be strengthen but not weaken. To represent this condition, it is better to introduce the constraint that a plant of only the existing plant type can be a candidate for the new plant. In other words, a coal power plant can be constructed in a place where a coal power plant is already located, but it cannot be located in a site with only gas power plants.

4. Methods

4.1. Multiregional optimal-generation planning model

(a) Summary of developed model

To analyze the optimal locations and scales of power plants, we developed a multiregional optimal-generation planning model that can simulate capacity, hourly/annual electricity and waste heat generation, and plant location, while minimizing total cost (capital cost, operation and maintenance cost, and fuel cost) under several constraints (Ashina and Fujino, 2008; Shiraki et al., 2012). These constraints include satisfying electricity demand and/or CO_2 emissions reduction targets. An image of our multiregional optimal-generation planning model is shown in Fig. 3. The model considers hourly electricity demand by prefecture and allows electricity interchange among 60 prefectures through hypothetical power transmission lines based on the actual power transmission network. The location of each power plant was set in accordance with actual situations, but capacities were determined via an optimization calculation. The plant-type constraint mentioned in section 3 was considered explicitly. Because Japan has four seasons and the demand pattern in each season is different, we classified daily demand fluctuations during one year into seven

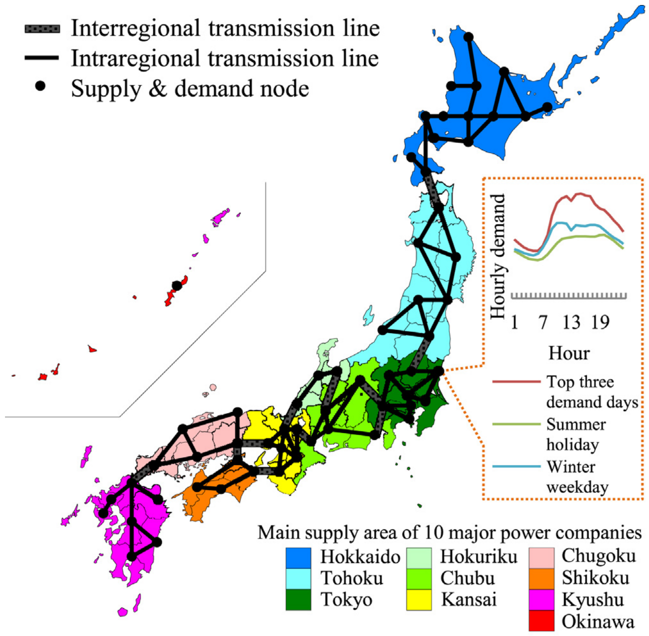


Fig. 3. Image of multiregional optimal-generation planning model.

representative days: a day representing the average power of top-three demand days, weekday in summer, holiday in summer, weekday in winter, holiday in winter, weekday in an intermediate season, and holiday in an intermediate season. Examples of the daily demand patterns are shown in Fig. 3.

The model was formulated as a linear programming problem using Python and simulated using the Gurobi Optimizer.

(b) Objective function and constraints

The objective function and constraints of the developed model are described below. The associated variables and indices are listed in Table 1. Upper-case letters represent endogenous variables, and lower-case letters represent exogenous variables and indices.

Objective function

The objective function of the developed model was to minimize discounted total system cost during the period 2010–2060. The discounted total system cost was calculated as the discounted sum of variable costs including fuel, generator capital, and capital for building inter-regional transmission lines. Future fuel costs were based on IEA data (2014) (see 4.2 (b)). Generator capital cost and generation efficiency were taken from the Energy and Environment Council (2011) (see Table 2). The capital cost of interregional transmission lines was taken from Ashina and Fujino (2008).

$$\mathrm{TOTLCOST} = \sum_{p}\Bigg[\{1/(1+d_{rate})\}^{p\bullet dt}\bullet\sum_{n=1}^{dt}\{1/(1+d_{rate})\}^{n} \bullet\Bigg\{\sum_{g,d,t,l} nd_{d}\bullet\left(vc_{p,g}\bullet O_{p,g,d,t,l}\big/ eff_{g}\right) + \sum_{g,l} fc_{p,g}\bullet C_{p,g,l} + \sum_{l,l'} tfc_{p,l,l'}\bullet TC_{p,l,l'}\Bigg\}\Bigg] \tag{1}$$

Constraints

Supply demand balances

Hourly electricity demand in prefecture should be satisfied by the hourly electricity generation in prefecture l and power transmission from other prefectures. Excess electricity generated in each prefecture should be stored or transmitted to other prefectures. Transmission loss was modeled as 1%/100 km of transmission distance (TEPCO, 2007).

$$\sum_{g}\left\{(1-ownuse_{g})\bullet O_{p,g,d,t,l}\right\} + \sum_{l'}\left\{(1-loss\_t_{l,l'})\bullet T_{p,d,t,l,l'}\right\} = demand_{p,d,t,l} + \sum_{l'} T_{p,t,l',l} + \sum_{gs} S_{p,gs,d,t,l} \tag{2}$$

Generation capacity constraints

Hourly generation should be less than the product of installed generation capacity and the upper limit of capacity factor (see Table 2). In this study, the upper limit of capacity factor for renewables was based on the input energy carrier. The hourly capacity factor of conventional hydro power was calculated using hourly water flow (Ashina and Fujino, 2008). For solar photovoltaics, we first estimated the hourly capacity factor by prefecture using insolation data from the prefectural capital (NEDO, 2012) and then classified daily patterns of the capacity factor into the seven representative demand days mentioned in Section 4.1(a). For wind power, we generated hourly wind patterns by region using average wind speeds and the Weibull coefficient for locations where wind power already exists or is planned (NEDO, 2006). For details of capacity factor estimation, see Shiraki et al. (2012).

$$O_{p,g,d,t,l} \le cf_{g,d,t}\bullet C_{p,g,l} \tag{3}$$

Load-following constraints

The load-following capability of each generator varies in relation to its heat capacity, economic performance, manipulation capabilities, and so on. In the developed model, hourly load-following capabilities were modeled using equation (4). The lower limit of output decrease rate *decrease*$_g$, and the upper limit of output increase rate *increase*$_g$, of each generator are listed in Table 2.

$$O_{p,g,d,t,l} - decrease_{g}\bullet C_{p,g,l} \le O_{p,g,d,t+1,l} \le O_{p,g,d,t,l} + increase_{g}\bullet C_{p,g,l} \tag{4}$$

Energy storage balances

The developed model assumed balanced daily generation from storage and daily charging of storage. Cycle efficiency eff_{gs} is listed in Table 2.

$$\sum_{t} O_{p,gs,d,t,l} = eff_{gs}\bullet\sum_{t} S_{p,gs,d,t,l} \tag{5}$$

Storage capacity constraints

Total daily charging should be less than the maximal storage capacity. The factor $maxstr_{gs}$was assumed to be 5 h.

$$\sum_{t} S_{p,gs,d,t,l} \le maxstr_{gs}\bullet C_{p,gs,l} \tag{6}$$

Table 1
Variables and indices.

(Endogenous variables)	
$TOTCOST$	Discounted total generation cost [$\$_{2010}$]
$O_{p,g,d,t,l}$	Output from generator g in prefecture l at time t on day d in period p [GW]
$C_{p,g,l}$	Capacity of generator g in prefecture l in period p [GW]
$TC_{p,l,l'}$	Capacity of transmission line from prefecture l to l' in period p [GW]
$T_{p,t,l,l'}$	Transmission from prefecture l to l' at time t in period p [GW]
$S_{p,gs,d,t,l}$	Charging to storage gs in prefecture l at time t on day d in period p [GW]
$C\_ADD_{p,g,l}$	Additional capacity of generator g in prefecture l in period p [GW]
$TC\_ADD_{p,l,l'}$	Additional capacity of transmission line from prefecture l to l' in period p [GW]
(Exogenous variables or assumptions)	
d_rate	Discount rate (=3%)
dt	Number of years in a period (=5)
nd_d	Number days for each representative days (top three demand days: 3, weekday in summer: 98, holiday in summer: 21, weekday in winter: 95, holiday in winter: 26, weekday in intermediate season: 97, holiday in intermediate season: 25)
$vc_{p,g}$	Unit variable cost of generator g in period p [$\$_{2010}$/GWh]
$fc_{p,g}$	Unit fixed cost of generator g in period p [$\$_{2010}$/GW]
$tfc_{p,l,l'}$	Unit fixed cost of transmission line from prefecture l to l' in period p [$\$_{2010}$/GW]
eff_g	Generation efficiency of generator g [%]
$ownuse_g$	Own use of generator g [%]
$loss\_t_{l,l'}$	Rate of transmission loss from prefecture l to l' [%]
$demand_{p,d,t,l}$	Electricity demand in prefecture l at time t on day d in period p [GW]
$cf_{g,d,t}$	Upper limit of capacity factor for generator g at time t on day d [%]
$decrease_g$	Lower limits of output decrease rate for generator g [%]
$increase_g$	Upper limits of output increase rate for generator g [%]
$loss\_c_{gs}$	Rate of charging loss for storage gs [%]
$maxstr_{gs}$	Maximum capacity of storage gs [hr] (= 5hr for pumped hydro)
$c\_dec_{p,g,l}$	Decommissioning capacity of generator g in prefecture l in period p [GW]
$upperFS_g$	Upper limits of additional capacity compere to existing capacity [%]
$cremax_{p,gr,l}$	Maximum capacity of renewables gr in prefecture l in period p [GW]
ccf_g	CO_2 capture rate from generator g [%]
$ccsmax_p$	Maximum capacity of CO_2 capture and storage in period p [t-CO_2]
$margin_r$	Capacity margin in region r (=8%)
$p\_demand_{p,r}$	Peak hourly demand in region r in period p [GW]
emf_g	CO_2 emission factor for generator g [t-CO_2/GWh]
(Indices)	
p	Period (1:2000, 2:2005, …, 11:2050)
g	Generator (1: Coal boiler, 2: Oil boiler, 3: Gas boiler, 4: Gas combined, 5: Conventional hydro, 6: Pumped hydro, 7; Nuclear, 8: Solar, 9: Wind)
$gs \in g$	Generator which can be a storage (6: Pumped hydro)
$gr \in g$	Generator using renewables (5: Hydro, 8: Solar, 9: Wind)
d	Representative days (1: top three demand days, 2: weekday in summer, 3: holiday in summer, 4: weekday in winter, 5: holiday in winter, 6: weekday in intermediate season, 7: holiday in intermediate season)
t	Time (1, 2, …, 24)
l	Prefectures (1: Hokkaido_Wakkanai, 2: Hokkaido_Rumoi, …, 60: Okinawa)
r	Region (1: Hokkaido, 2: Tohoku, …, 10: Okinawa)

Transmission capacity constraints

The Japanese power grid has two frequencies (50 Hz in eastern Japan, and 60 Hz in central and western Japan), and the capacities of the frequency changers (1.2 GW in total) that connect the areas are not large compared to peakelectricity demand (METI, 2011b). In addition, there are 10 major electric companies in Japan, and each company mainly supplies its original supply area. Thus, interregional transmission capacities have not been developed sufficiently. To consider these characteristics of Japan's power grid, constraints of

Table 2
Generator parameters.

	Abbreviations	$fc_{p,g,r}$ [$\$_{2010}$/W]	eff_g	$Own\ use_g$	$cf_{g,t}$	$Increase_g$ $decrease_g$	$Lifetime_g$ [yr]	emf_g [t-C/MWh-th]
Coal boiler	COL	230	40-48%	6%	78.6%	26%, 31%	40	0.089
Coal boiler w/CCS[a]	COL_CCS	424	40-48%	28%	78.6%	26%, 31%	40	
IGCC[b]	IGCC	320	40-48%	15%	78.6%	30%, 91%	40	
IGCC w/CCS[a]	IGCC_CCS	387	40-48%	25%	78.6%	30%, 91%	40	
Oil boiler	OIL	190	36-39%	5%	79.8%	45%, 31%	50	0.067
Gas boiler	GAS_BLR	190	38-39%	4%	81.7%	41%, 46%	40	0.049
NGCC[c]	NGCC	120	45-57%	2%	83.9%	30%, 91%	40	
NGCC w/CCS	NGCC_CCS	245	45-57%	16%	83.9%	30%, 91%	40	
Conventional hydro	HYD_CNV	–	100%	–	78.1%	*[d]	100	–
Pumped hydro	HYD_PMP	600	65%	–	95.0%	100%, 100%	100	–
Nuclear	NUC	380	33%	4%	78.1%	0%, 0%	40	–
Solar photovoltaics	SOL	450–224	–	–	*[d]	*[e]	20	–
Wind power	WIN	275–264	–	–	*[d]	*[e]	20	–

[a] We assumed that 90% of CO_2 emission is captured by CCS.
[b] Integrated coal Gasification Combined Cycle.
[c] Natural gas Combined Cycle.
[d] Depend on the region (Shiraki et al., 2012).
[e] Defined based on hourly input energy.

interregional transmission lines must considered. We explicitly modeled the capacity of interregional transmission lines and assumed that hourly power transmission should be less than the capacity of any interregional transmission line. The capacities of existing interregional transmission lines were taken from Kainou (2005).

$$T_{p,t,l,l'} \le TC_{p,l,l'} \quad \text{where } l \in r,\ l' \in r' \tag{7}$$

Dynamic capacity balances

Generator lifetimes were considered explicitly. Existing generators scheduled for retirement would be decommissioned. The lifetime of each generator is listed in Table 2. Total transmission capacity in period p was calculated as the sum of the transmission capacity in period p-1 and the added transmission capacity in period p.

$$C_{p,g,l} = C_{p-1,g,l} + C\_ADD_{p,g,l} \bullet dt - c\_dec_{p,g,l} \bullet dt \tag{8}$$

$$T_{p,l,l'} = TC_{p-1,l,l'} + TC\_ADD_{p,l,l'} \bullet dt \quad \text{where} \quad l \in r, l' \in r' \tag{9}$$

Dynamic fuel switching constraints

According to historical trends of power plant development in Japan, drastic fuel switching has not occurred. This is because of several factors: speed of power plant construction, existence of infrastructure such as fuel-receiving terminals, fund-raising capability, capacity of fuel-exporting countries, and so on. These factors are crucial for fossil-fuel power generation because any power-consuming entity needs not only generation plants but also consistent fuel supply. In this model, we assumed that additional coal and gas power-generation capacity is constrained by the coal and gas power-generation capacity in the previous period. We estimated the coefficient $upperFS_g$as 7% for coal boilers and 4% for gas boilers by using equation (10) and historical capacity data from 1990 to 2010 (METI, 2011a, 2011b).

$$\sum_{l} C\_ADD_{p,g,l} \le upperFS_g \bullet \sum_{l} C_{p-1,g,l} \tag{10}$$

Technological potential of renewables

Total installed capacity of renewables should be less than their respective technological potentials. The technological potentials of solar photovoltaics and wind power were taken from Shiraki et al. (2012) (see Table 3). Most of Japan's hydropower potential has already been developed. Thus, we assumed that the technological potential for hydropower was equal to the existing capacity.

$$C_{p,gr,l} \le cremax_{p,gr,l} \tag{11}$$

Capacity margin constraints

To account for unpredictable demand changes or accidents at generation sites, power suppliers should have some capacity margin. We assumed that each region needs a capacity margin equaling 8% of the peak demand.

$$\sum_{g,l \in r} \left(cf_{g,t} \bullet C_{p,gc,l} \right) > (1 + margin_r) \bullet p\_demand_{p,r} \tag{12}$$

CO_2 emissions targets

CO_2 emissions from the power sector in period p should be lower than the emission reduction targets, which were set based on a scenario assumption (see 4.2 (b)).

$$\sum_{g,d,t,l} \left(nd_d \bullet emf_g \bullet O_{p,g,d,t,l} \big/ eff_g \right) - \sum_{g,d,t,r} \left(nd_d \bullet ccf_g \bullet O_{p,g,d,t,l} \big/ eff_g \right) \le emsmax_p \tag{13}$$

(c) Advantages and limitations of model

Three features of the developed model, spatial resolution, time resolution, and optimization method, offer advantages and limitations.

National- and/or regional-scale models, which divide Japan into about 10 regions, are mainly used for power system analysis in Japan. These models are not detailed enough for location analysis of power plants, although these models are available to estimate the generation mix in a particular place. Our model divides Japan's power grid into 60 prefectures. It can identify the prefecture in which a power plant should be located. However, the model cannot identify the specific locations of power plants and industrial symbiosis complexes below the prefecture level owing to limited spatial resolution. Even so, the spatial resolution is adequate for discussing prefecture-level waste heat potential because most power plants and energy-intensive industries in Japan are located close to the coastal area, especially near large industrial ports.

The model includes hourly supply–demand balance constraints for electricity. Thus, hourly variation of electric power demand and output fluctuation from renewables can be considered. For waste heat, we simply assumed that the amount of the waste heat from power plants is related to generation by power plants. In a future study, we will incorporate hourly heat demand and consider the hourly supply–demand balance for waste heat.

There are two methods for dynamic optimization, namely, intertemporal optimization and recursive dynamic optimization. The former method assumes that decision makers decide on capital investment and operation for an entire analytical period at once. The latter assumes that decision makers decide on capital investment and operation year-by-year over the entire analytical period. In other words, the former method assumes that decision makers have a long-term outlook, and the latter method assumes them to be myopic. Both methods are unrealistic in some manner. Investment decisions based on the former method might be unrealistically efficient because it assumes perfect foresight, that is, the decision maker has perfect knowledge of future electricity demands and fuel prices. In contrast, investment decisions based on the latter method might be unrealistically inefficient because it assumes that future information is totally unknown to the decision maker. The former method is often adopted for electricity system analysis because the power industry tends to invest based on long-term predictions of electricity demands and fuel prices. In the model developed in the study, we estimate future power systems by intertemporal optimization.

4.2. Case setting

To consider future uncertainties in Japan's electricity system, we developed 12 cases that depended on the following parameters: demand growth rate, regional distribution of demand, and CO_2 emissions reduction targets. The use of nuclear power plants,

Table 3
Technological potential of renewables (Shiraki et al., 2012).

Region	Prefecture[a]	Potential [MW]		Region	Prefecture	Potential [MW]	
		Solar	Wind			Solar	Wind
Hokkaido[a]	Wakkanai	383	1625	Hokuriku	Ishikawa	2622	288
	Rumoi	374	1612		Fukui	966	148
	Abashiri	1073	4288	Chubu	Nagano	8363	137
	Asahikawa	1105	3951		Gifu	3003	596
	Nemuro	334	1366		Shizuoka	5940	686
	Kushiro	634	2405		Aichi	7159	529
	Obihiro	1111	4344		Mie	3460	1024
	Iwamizawa	726	2630	Kansai	Shiga	1396	513
	Sapporo	1533	1420		Kyoto	2406	673
	Urakawa	453	1930		Osaka	5005	86
	Kucchan	142	163		Hyogo	4722	750
	Hakodate	543	1579		Nara	1930	353
	Esashi	247	1055		Wakayama	1803	730
	Muroran	520	1483	Chugoku	Tottori	1760	187
Tohoku	Aomori	5927	5376		Shimane	2723	447
	Iwate	6125	4628		Okayama	4835	199
	Miyagi	5165	943		Hiroshima	5269	452
	Akita	3522	4688		Yamaguchi	3282	542
	Yamagata	3369	1950	Shikoku	Tokushima	2034	184
	Fukushima	11667	2495		Kagawa	2250	42
	Niigata	4923	1170		Ehime	4205	315
Tokyo	Ibaraki	10286	246		Kochi	1810	535
	Tochigi	4447	73	Kyushu	Fukuoka	5246	217
	Gunma	6063	49		Saga	2327	194
	Saitama	7595	16		Nagasaki	4949	794
	Chiba	9454	190		Kumamoto	5032	1028
	Tokyo	7942	161		Oita	3596	653
	Kanagawa	5837	28		Miyazaki	2515	1025
	Yamanashi	2581	21		Kagoshima	4906	2360
Hokuriku	Toyama	1208	35	Okinawa	Okinawa	1538	2962

including resumption of operations at existing nuclear power plants, has been under discussion since the Fukushima Daiichi nuclear disaster of March 2011. Nuclear power is positioned as an "important base load electricity source based on the premise of ensuring safety" in the 4th Basic Energy Plan passed by the cabinet in April 2014. Although there was no operational nuclear power plant in Japan in June 2015, a few nuclear power plants were under safety review for possible resumption of operations. Based on this situation, we assumed that in all 12 cases, existing nuclear plants would resume operation, but no new construction would be allowed.

In addition to the above 12 cases, we assumed *no* renewable development cases in our assessment of the impact of regional deployment of renewables.

(a) Electricity demand cases (4 cases)

The scale of regional electricity demand depends on the selected technology and energy consumption habits. For example, increase in the use of electric vehicles and electric heat-pump water heaters will result in increased electricity demand, while widespread adoption of energy-saving practices may decrease electricity demand. Moreover, the scale of regional electricity demand would affect the location of new power plants as existing fossil-fuel power plants aggregate their capacity and undergo decommissioning. Therefore, we based four cases of electricity demand on the parameters of demand growth rate and regional demand distribution.

As described in section 1, electricity generation from fossil-fuel power plants is projected to decrease owing to greenhouse gas emissions reduction targets. Because this would lead to decreased fossil-fuel power capacity requirement, existing fossil-fuel power plants could be aggregated into particular regions. In the aggregation process, the economic factors discussed in section 3 would be the most relevant for selecting plant location because the existing sites have already passed the social and regulatory screens. Because transmission losses, which directly affect transmission costs, are proportional to the distance between the power production and consumption sites, uncertainties in regional electricity demand should be considered when selecting power plant location based on economic factors. Two factors, namely, growth rate and regional electricity demand distribution, were found to influence electricity demand in each region. Regional demands were determined using equation (14):

$$\sum_t demand_{p,t,r} = \left(\frac{\sum_t demand_{1,t,r}}{pop_{1,r}}\right) \bullet (1+\alpha)^{p \bullet dt} \bullet pop_{p,r}, \tag{14}$$

where $pop_{p,r}$is the population of region r in period p, and $\alpha$is the annual growth rate of electricity demand per capita.

For demand growth rate per capita, we created two cases: annual growth of 0.2% and 1.0%. Total electricity demand over the years 2000–2050 for each case is shown in Fig. 4. The former case was based on the increase in electricity demand per capita from 2005 to 2010 (METI, 2011a). This case assumed that the trend in electrification before the Fukushima accident would not change, and the growth rate would remain the same until 2050. In this case, although electricity demand per capita would increase, total electricity demand in 2050 would decrease to about 700 TWh from 840 TWh in 2010 owing to population decrease. The latter case assumed that electrification would increase in accordance with the adoption of electric technologies such as electric vehicles and heat-pump water heaters. Total electricity demand in this case would reach about 960 TWh in 2050.

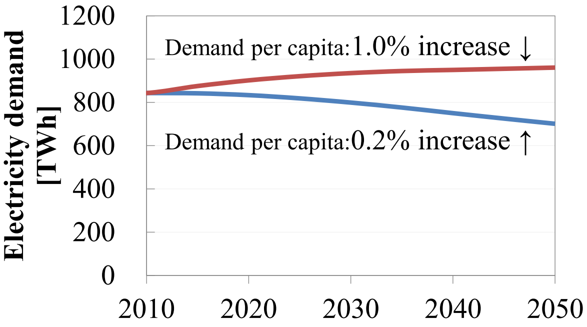


Fig. 4. Total electricity demand by case.

To calculate the regional electricity demand distribution, we assumed that regional electricity demand would be affected by regional population. We created 2 cases: aggregation case (A) and keeping-base-year case (B). In Japan, the population tends to aggregate in the Tokyo metropolitan area. The National Institute of Population and Social Security Research (IPSS) estimated future population by region considering current domestic migration trends (IPSS, 2013). The regional population for the aggregation case was adopted from an IPSS estimate. In addition, IPSS estimated future regional populations without domestic migration. In this estimate, future regional populations were assumed to be influenced not by domestic migration but by births and deaths. The regional population for the keeping-base-year case was taken from this estimate. The quotients of demand in the keeping-base-year and the aggregation cases are shown in Fig. 5. Electricity demand in the Tokyo region in the aggregation case would be less than 95% of that in the keeping-base-year case, because of the assumption of no domestic migration in the latter case.

In the light of the two growth-rate cases and the two regional population cases, we created 4 demand cases, namely, 02A, 02B, 10A, and 10B.

(b) CO_2 emissions reduction cases (3 cases)

In 2009, the Group of Eight pledged in L'Aquila, Italy to support a global long-term target to achieve 50% reduction in greenhouse gas emissions by 2050 (G8 L'Aquila Summit, 2009). Japan has a national long-term target to achieve an 80% reduction in greenhouse gas emissions from the current levels by 2050 (Japan–U.S. Summit Meeting, 2009). There is no explicit long-term target for the power sector because uncertain electricity demand and electricity supply obligations make it difficult to set a power-sector-specific target. However, it is clear that power sector needs to reduce its greenhouse gas emissions drastically to meet global and national emissions reduction targets. To assess the impact of long-term emissions reduction targets, we created 2 cases of CO_2 emissions reduction in the power sector: a 50% emissions reduction case (50%) and an 80% emissions reduction case (80%). These cases assumed that the power sector would reduce its CO_2 emissions by 50% and 80%, respectively, compared to 1990 levels. Moreover, we set no emissions reduction case (Base) with the assumption of no emissions reduction target.

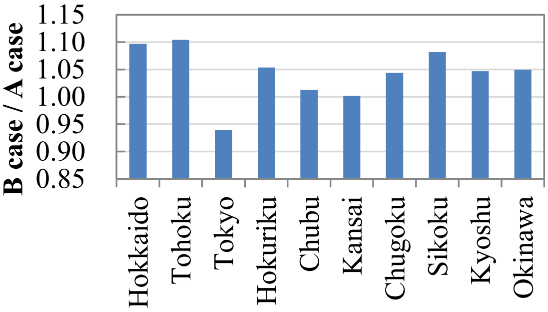


Fig. 5. Quotient of regional demand cases.

The probability of these cases can be related to global emission mitigation trends. If there are strong trends in climate change mitigation globally, the Japanese power sector will be under pressure to reduce its greenhouse gas emissions, and if no such trends emerge, the Japanese power sector will experience little pressure to reduce its emissions. Moreover, global mitigation activities would affect the future prices of fossil fuels. Thus, fossil fuel prices in the abovementioned three emissions cases are not identical. The IEA (2014) estimated fossil fuel consumption rates and prices under several mitigation scenarios. Their 6 °C Scenario (6DS) assumed no reduction in emissions, 4 °C Scenario (4DS) assumed countries would cut their emissions as stated, and the 2 °C Scenario (2DS) assumed a sustainable energy system and a consequent reduction in greenhouse gas emissions. Therefore, fossil fuel prices in the no emissions reduction case, 50% reduction case, and 80% reduction case were based on Japanese fossil fuel prices in the 6DS, 4DS, and 2DS scenarios, respectively.

(c) No additional renewable case

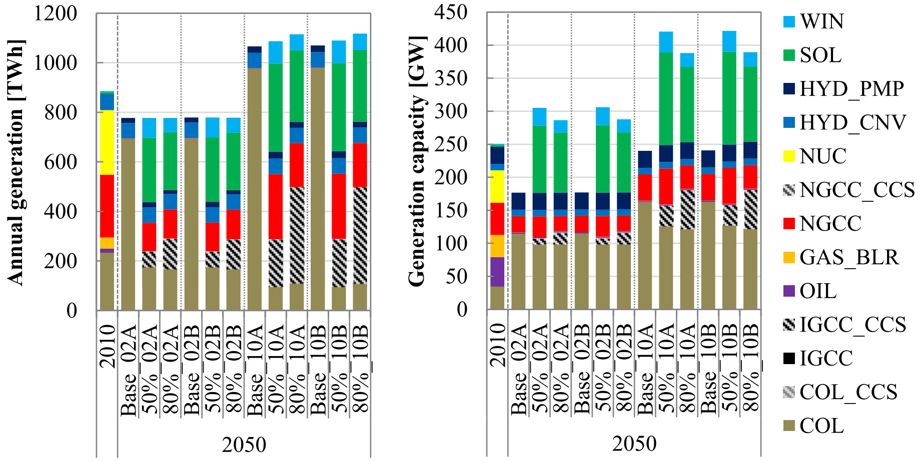
To assess the impact of renewable energy development considering the 80% emissions reduction target, we created a case that does not allow the installation of additional renewable capacity in the 12 aforementioned cases. The use of CCS technologies and fuel switching among fossil fuels would be the only options for reducing CO_2 emissions in these cases.

5. Results

5.1. Results of Japanese power grid in 2050

Annual generation mixes projected for 2050 by case are shown in Fig. 6 (a), which includes the generation mix for the year 2010 as a reference. In the cases that assumed a 0.2% increase in electricity demand per capita, annual electricity generation would decrease to about 780 TWh in 2050 from 880 TWh in 2010. In the cases that assumed a 1.0% increase in electricity demand per capita, however, annual electricity generation would increase to about 1100 TWh in 2050. These annual generation figures are 11%–15% higher than the annual electricity demand shown in Fig. 4 owing to transmission loss, electricity use in power plants, and cycle loss of charging.

In the cases of no emissions targets, almost 90% of total generation would come from coal-fired power plants. In the cases with emissions reduction targets, fossil-fuel power plants would account for 45%–60% of total generation. The generation share of solar photovoltaic and wind power in these cases would reach 32%–44%. There were no significant differences between the 50% emissions reduction cases and the 80% emissions reduction cases. This was because renewables, which could supply electricity at lower cost than integrated coal gasification combined cycle (IGCC) power plants with CCS facilities, would have been installed in the 50% emissions reduction cases. Thus, most of the additional reduction in the 80% emissions reduction cases compared to the 50% emission reduction cases would come from IGCC power plants with CCS. Annual sequestered CO_2 in the year 2050 in the 50%_10A and 80%_10A cases would reach 40 Mt–C (146 Mt–CO_2) and 80 Mt–C (296 Mt–CO_2), respectively.



(a) Annual generation mix (b) Generation capacity

Fig. 6. Generation mix and capacity in 2010 and in 2050 by case.

Total generation capacities in the years 2010 and 2050 by case are shown in Fig. 6 (b). In the Base_02A and the Base_02B cases, total generation capacity in 2050 decreased by 30% compared to that in 2010. In the base cases, coal-fired power plants accounted for 80%–85% of total generation capacity. A few NGCC power plants that are already planned would be built but not be used fully in the base cases because of the absence of emissions targets and the assumption that natural gas prices would increase. In the cases with emissions reduction targets, the installed capacities of solar photovoltaics and wind power would reach 91–140 GW and 19–31 GW, respectively. Total generation capacities in these cases were 1.2–1.7× the capacities in the year 2010 owing to a massive increase in installed renewable capacity. Total generation capacities in the 80% emissions reduction cases were lower than the total generation capacities in the 50% emissions reduction cases. This was because IGCC with CCS would supply the electricity that solar photovoltaics would have supplied in the 50% emissions reduction cases, and the capacity factor of IGCC is higher than that of solar photovoltaics.

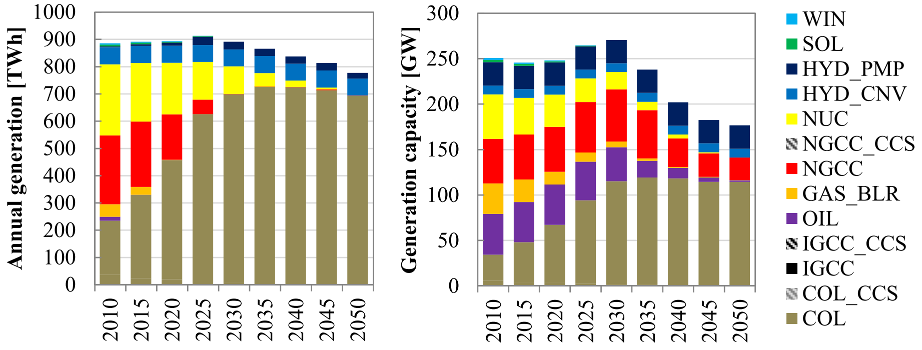
5.2. Time series analysis

The time series of annual generation in the Base_02A case is shown in Fig. 7 (a). In this case, generation from coal-fired power plants would increase and would eventually replace generation from nuclear and natural gas power plants. Coal generation would supply almost 90% of the electricity demand after 2040.

The time series of generation capacity in the Base_02A case is shown in Fig. 7 (b). Although a few natural gas and oil fossil-fuel power plants would continue to operate, these power plants would not operate at their capacity owing to higher fuel prices than coal.

The time series of annual generation in the 80%_02A case is shown in Fig. 8 (a). This time series would be similar to that of the Base_02A case until 2040. After 2040, generation from IGCC with CCS would increase gradually. Then, solar photovoltaic and wind power would increase significantly by 2050, and their share in generation would exceed 40%.

The time series of generation capacity in the 80%_02A case is shown in Fig. 8 (b). The model estimated that 90 GW of solar photovoltaic capacity would be installed from 2045 to 2050, that is, an average annual increase of 18 GW, which would be the most cost effective way to achieve the 80% CO_2 emissions reduction target by 2050. This would appear as an extreme result if we consider historical data on annual photovoltaic installation. For example, Spain and Italy experienced a boom in photovoltaic deployment under the strong Feed-in Tariff policy in 2009 and 2011, but the annual installed capacities in those countries at that time were approximately 6 GW and 9 GW, respectively (EPIA, 2014). If this result is deemed infeasible, we should model the upper limit of annual



(a) Annual generation (b) Generation capacity

Fig. 7. Time series results of Base_02A case.

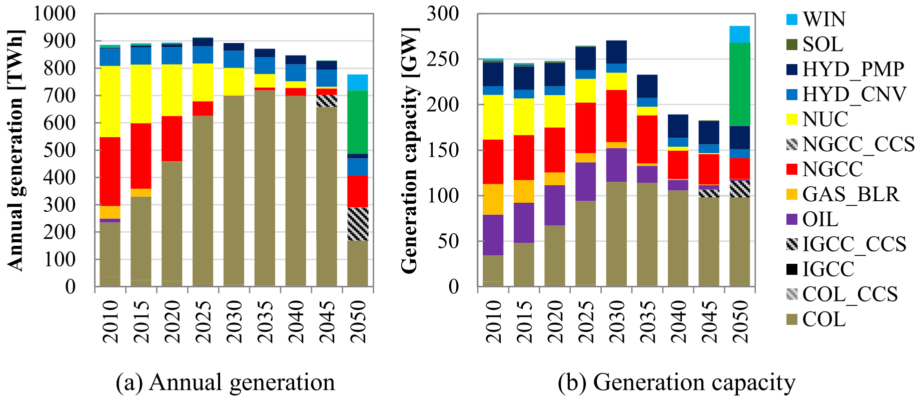


Fig. 8. Time series results of 80%_02A case.

installed capacity using additional constraints. However, annual deployment of 18 GW of solar photovoltaic capacity should not be deemed “technologically infeasible” because 38 GW of photovoltaic capacity was installed globally in 2013 (EPIA, 2014). Thus, we did not constrain the annual installed capacity. The possibility of this extreme result under certain global mitigation actions could not be assessed in this study because the model focused only on the Japanese electricity grid. In future, we will consider global solar photovoltaic capacity deployment using the global-scale energy system model.

A drastic increase in photovoltaic generation within a short period would raise another issue. It would cause annual generation from coal-fired power plants to drop drastically during 2045–2050, while most of the capacity would still be available in 2050 (Fig. 8). As a result, in 2050, most coal power plants would be idle. The output duration curves for coal power plants in 2045 and 2050 are shown in Fig. 9. These curves were generated by arranging the estimated hourly outputs of coal power plants in decreasing order. The colored areas in the graph indicate the connected capacities of coal power plants in 2045 and 2050, classified by year of installation. The newer installed capacity is shown at the bottom of the graph. Because there would be no additional capacity from coal-fired plants after 2035 and all capacity installed before 2010 would have been decommissioned before 2040, the connected capacity of coal power plants in 2045 and 2050 would be identical. In general, newly installed power plants tend to operate preferentially, so the power plants under the output duration curve are the power plants that operate in each hour. In 2045, most of the power plants installed between 2015 and 2030 would be fully operational. The power plants installed by 2010 would operate only during periods of high demand, and their capacity factor in 2045 would be only 5%. In 2050, the output duration curve would trend strongly downward. The average capacity factors in 2050 for plants installed in 2030, 2025, and 2020 would be 72%, 46%, and 9%, respectively. The capacity factor for plants installed before 2020 would be less than 1%. These results indicate that especially for power plants installed in 2025, 31 GW of generation capacity would be fully operational only for half of their lifetime. The depreciation period for all these power plants would have been achieved by 2050 because the depreciation period for fossil-fuel power plants was set to 15 years in this study. Therefore, they could be decommissioned in 2050 from the viewpoint of accounting, even plants that are technically available. However, if some industrial symbiosis complexes were to use waste heat from these fossil-fuel power plants, this strategy should be avoided to lessen the uncertainty of heat supply resources.

The results indicate that the installation of 90 GW of solar photovoltaic capacity and the sudden drop in coal-fired generation from 2045 to 2050 would be cost effective only if there were long-term emissions reduction targets. However, it is unclear whether this drastic installation of solar photovoltaic capacity is possible. In addition, from the viewpoint of industrial symbiosis complex development, sudden decommissioning of fossil-fuel power plants should be avoided to sustain their energy symbiosis. It is better to take early action by setting mid-term emissions reduction targets than setting only long-term targets.

5.3. Location of fossil-fuel power plants in 2050

(a) Impact of emissions reduction targets on fossil-fuel power plant siting

Prefecture-wise fossil-fuel-based power generation in 2010 and in the Base_02A case, 50%_02A case, and 80%_02A case for 2050 are

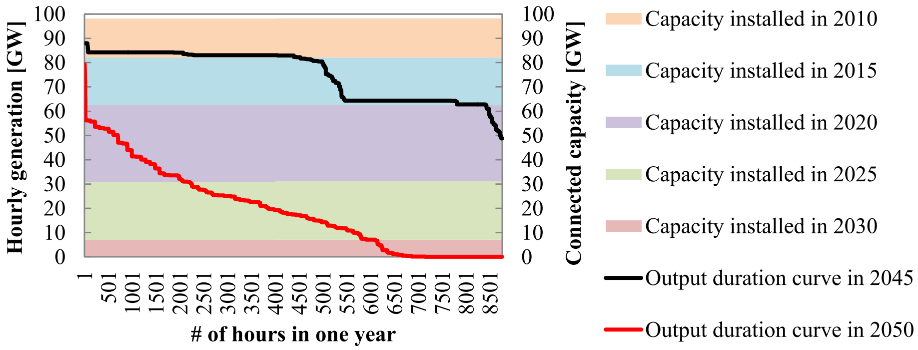


Fig. 9. Output duration curve and connected capacity by installation year for coal fossil-fuel power plants in CO280_02A case.

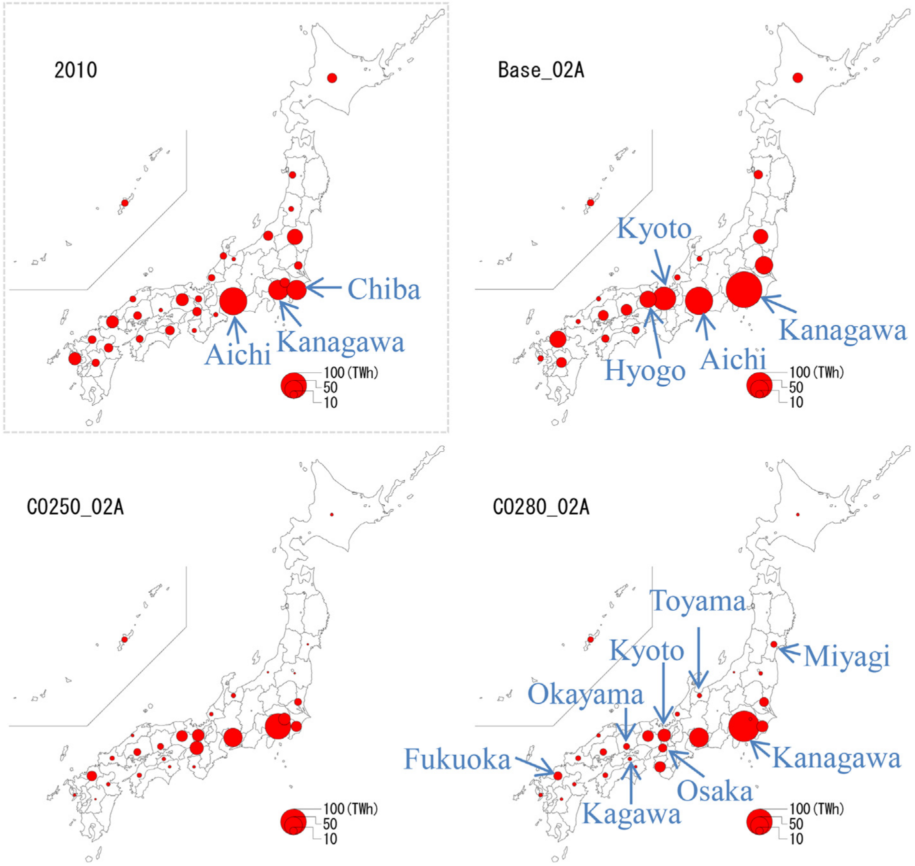


Fig. 10. Electricity generation by fossil-fuel power plants by prefecture and emission case (Demand case: 02A).

shown in Fig. 10. While fossil-fuel power plants were located mainly in the coastal prefectures in 2010, in 2050, power plants would be aggregated into particular prefectures. In the Base_02A case, regional electricity generation from fossil-fuel power plants is proportional to regional electricity demand because there would be no nuclear power plants, no solar, and no wind. In the Kanto region, Kanagawa (next to Tokyo) would be a major electricity supplier in 2050 and would generate 193 TWh, which is 1.44× the total electricity generation in the Kanagawa, Tokyo, and Chiba prefectures in 2010. Although the share of nuclear power was relatively high in the Kansai region in 2010, it would decrease in accordance with the decommissioning of existing nuclear plants. As a result, electricity generation from fossil-fuel power plants in the Kyoto and Hyogo prefectures would increase to 82 TWh and 43 TWh, respectively, from the 2010 levels of 8 TWh and 25 TWh.

In the emissions reduction cases, electricity generation from fossil-fuel power plants in each region would decrease owing to the installation of solar photovoltaics. In the Hokkaido and Tohoku regions, electricity generation from fossil-fuel power plants would drop by 10%–20% because these regions have high potential for inexpensive wind power generation. At the prefecture level, electricity generation from the following prefectures would increase from 2010 levels: Miyagi, Kanagawa, Toyama, Kyoto, Osaka, Okayama, Kagawa, and Fukuoka. All these prefectures either are close to major demand sites or have centers of major electricity demand.

These results revealed two findings concerning interregional and intraregional aspects of the Japanese power grid under the emissions reduction targets. The interregional comparison showed that fossil-fuel power plants would be developed in regions that have little wind power potential compared to their electricity demand, such as Tokyo, Chubu, and Kansai. In terms of the intraregional aspects, fossil-fuel power plants would be constructed near areas of major electricity demand in each region. It is expected that fossil-fuel power plants would continue to operate in these prefectures even under the emissions reduction targets.

(b) Impact of electricity demand on power grid

The ranges of uncertainty due to the demand cases for annual generation from fossil-fuel power plants in 2050 are shown in Fig. 11. Only prefectures with fossil-fuel power plants are represented on the graph. The bar chart shows annual generation in 2010, and the red bar shows median generation in 2050 for the four demand cases. The range of uncertainty in regions with the highest electricity demand, such as Tokyo, Chubu, and Kansai, which include three major metropolitan areas (Tokyo, Aichi, and Osaka), is higher than that in the other regions. In the emissions reduction cases, increases in wind power generation in the Hokkaido and Tohoku prefectures would be robust, causing generation from fossil-fuel power plants to decrease to almost zero. There were few uncertainties in the electricity demand cases in these prefectures, except for Miyagi and Fukushima. Because Miyagi is a major electricity demand site in the Tohoku region, fossil-fuel power plants would generate between 0.7 TWh and 6.9 TWh in the emissions reduction cases. In the Fukushima prefecture, generation by fossil-fuel power plants is affected strongly by the electricity demand cases. While fossil-fuel power plant generation in Fukushima would be 3.2 TWh in the 02A cases, it would reach 12.0 TWh in the 10B cases.

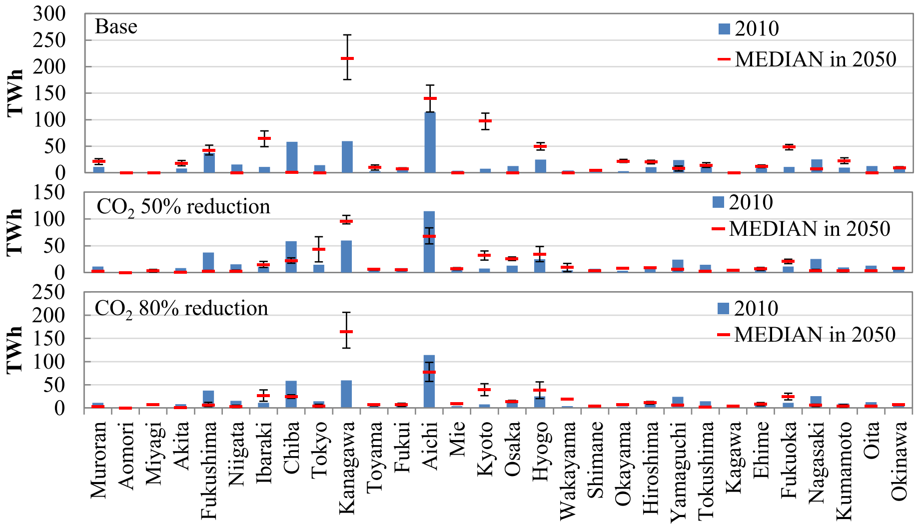


Fig. 11. Annual generation from fossil-fuel power plants by prefecture.

Because most of the Tohoku region is a subpolar zone, utilization of waste heat here may be the key for reducing CO_2 emissions from space and water heating, as well as from industrial symbiosis complexes. Thus, industrial symbiosis complexes should be considered in city planning for this region. The results of this study would support the siting of fossil-fuel power plants in these regions to encourage stable and sustainable demand for waste heat from fossil-fuel power plants.

5.4. Results of no additional renewables case

Estimated annual generation mixes in 2050 under the 80% emissions reduction targets in the no additional renewable cases (NO RE) are shown in Fig. 12. For comparison, the 80% emissions reduction cases with additional renewables (80%_02A, 80%_02B, 80%_10A, and 80%_10B) are denoted "with RE." In the no additional renewables cases, IGCC with CCS would generate the electricity that solar photovoltaics and wind would generate otherwise. Annual generation in the no additional renewables case would be 10%–12% higher than that in the case with renewables owing to the additional energy used for CCS. Annual sequestered CO_2 in 2050 in the no additional renewables in the 10A demand case would reach 210 Mt–C (770 Mt–CO_2).

The quotients of fossil-fuel power generation by region in the NO RE case and those in the RE case are shown in Fig. 13. The red bars show the average of the four cases, and the black lines indicate the range of uncertainties by case. Because of the wind power capacity in the Hokkaido and Tohoku regions in the RE cases, fossil-fuel power generation in these regions in the no RE cases would be about 8–4.2× higher than that in the RE cases. These results indicate that generation from fossil-fuel power plants in a region of high renewable potential would depend highly on the availability of renewables, even under the same emissions reduction targets.

5.5. Effects on industrial symbiosis planning

Here, we consider the implications of the results of generation planning. There were two implications for industrial symbiosis planning: optimal location and CO_2 emission reduction potential.

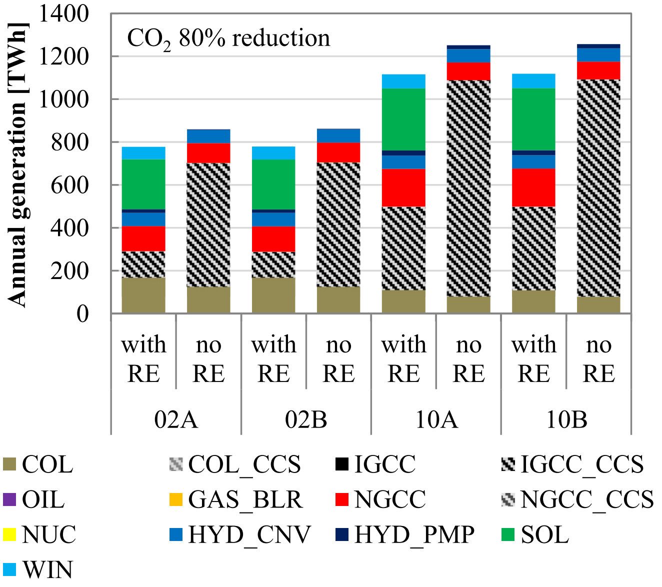


Fig. 12. Annual generation: With RE and No RE.

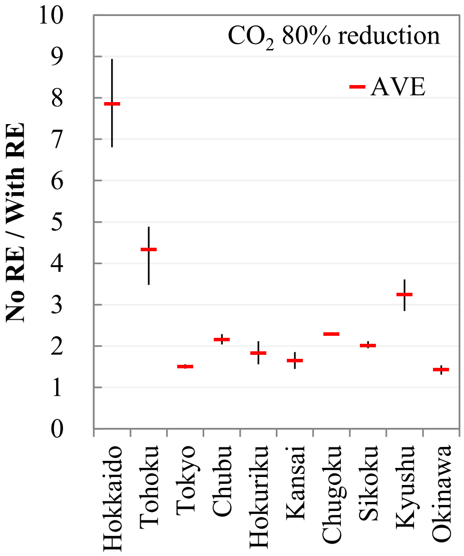


Fig. 13. Quotients of fired power generation.

(a) Optimal location of industrial symbiosis complex

As discussed in 5.2, generation from fossil-fuel power plants would drop drastically by 2050 only if there are long-term emission reduction targets. It is necessary to develop industrial symbiosis complexes near fossil-fuel power plants that would be operational until 2050 to sustain waste heat utilization. According to the results in 5.3, fossil-fuel power plants in regions with high electricity demand and low wind potential (i.e., Tokyo, Chubu, and Kansai) would operate until 2050, and generation and waste heat potential in these regions would be higher than the current levels. Especially, the waste heat utilization potentials in the Kanagawa, Aichi, and Hyogo prefectures would be high because many steel manufacturing plants and oil refineries are located in these prefectures. Thus, it is rational to prepare for waste heat utilization in these prefectures when updating energy-intensive facilities or developing new plants.

In addition, the potential of using waste heat from fossil-fuel power plants would be affected by electricity demand and availability of renewables (see 5.3 and 5.4). Especially, northern Japan would be highly affected by the availability of renewables because this region has high wind potential, although there is a large heat demand. It is effective to develop industrial symbiosis complexes in these regions if the renewables capacity is not increased drastically.

(b) CO_2 emission reduction potential of industrial symbiosis

Industrial symbiosis is expected to lead to reduction of primary energy consumption and improvement of air quality. However, the impact of CO_2 emissions reduction depends on the fuel used in power plants and heat supply systems for steam supply. Jacobsen (2006) reported that emissions reduction of 26 kt-CO_2/year could be achieved by using the waste heat from a 1300 MW coal power plant in Kalundborg, Denmark, and TEPCO (2007) estimated that steam supply from a 1500 MW gas combined cycle power plant in Kawasaki, Japan, could reduce CO_2 emissions by 25 kt/year. However, Chertow and Lombardi (2005) found that steam supply from a 454 MW coal-fired power plant would increase CO_2 emission by 51 kt compared with a conventional system. This was because this system supplies steam not by using waste heat but by steam extraction and the CO_2 intensity of fuel increases by switching the energy source of steam from heavy oil to coal. Thus, it is necessary to utilize waste heat from low-carbon-intensity power plants, namely, gas combined cycle and coal power plants with CCS technologies, and consider an adequate steam supply system to realize CO_2 emissions reduction by industrial symbiosis. However, coal power plants would be developed only if there are long-term emission reduction targets, as described in 5.2. Hence, it is important to set mid-term emissions reduction targets for encouraging the development of low-carbon power plants and accelerating waste heat utilization from said plants.

6. Conclusions

In this study, we used a quantitative model to analyze optimal locations and scales of power plants for reducing the fossil carbon consumption of Japan's power sector and for assessing the impact of those locations and scales on plans for industrial symbiosis complexes. The principal results of this study are as follows:

- Electricity generation from fossil-fuel power plants would amount to 90% of total generation in the no emissions reduction cases. Although emissions reduction targets would reduce generation from fossil-fuel power plants, almost half of the total generation would still come from fossil-fuel power plants in 2050 if CCS technology were to be available widely.
- From the time series analysis, the installation of 90 GW of solar photovoltaic capacity and the sudden drop in coal-fired generation between 2045 and 2050 would be cost effective only if there were long-term emissions reduction targets. However, sudden decommissioning of fossil-fuel power plants would adversely affect the decision to develop industrial symbiosis complexes. Considering this, setting mid-term emissions reduction targets should be preferred over setting only long-term targets.
- An interregional comparison showed that fossil-fuel power plants would be developed in regions that have little wind power potential compared to electricity demand, such as the Tokyo, Chubu, and Kansai regions.
- From an intraregional perspective, fossil-fuel power plants would be aggregated in areas near major electricity demand, such as the Miyagi, Kanagawa, Toyama, Kyoto, Osaka, Okayama, Kagawa, and Fukuoka prefectures.
- Fossil-fuel power generation in the Hokkaido and Tohoku regions in the no additional renewables cases would be about 4–8x times higher than that in the with-renewables cases because considerable wind power capacity would be installed in these regions if additional renewables were to be available. Generation from fossil-fuel power plants in the regions with high renewable potential would be highly dependent on the availability of renewables, even under the same emissions reduction targets.

It is concluded that industrial symbiosis complexes using waste heat from fossil-fuel power plants should be developed in regions/prefectures of high electricity demand because fossil-fuel power plants in these areas would be operational even with the 80% emissions reduction target. Planning for industrial symbiosis complexes in areas having with renewable potential or uncertain electricity demand should consider such factors. It is preferable to set clear mid-term emissions reduction targets in addition to long-term targets. This would reduce the uncertainty of heat demand and capacity, and avoid the sudden decommissioning of fossil-fuel power plants.

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