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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,

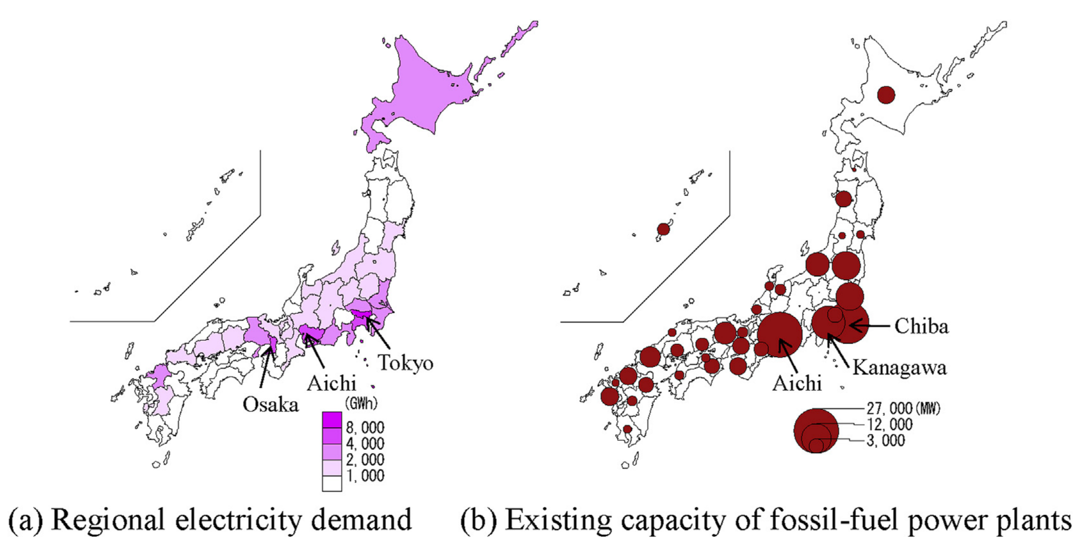

Fig. 1. Status of Japanese power sector in 2010.