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# Assessment of renewable energy expansion potential and its implications on reforming Japan's electricity system

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ABSTRACT

This study assesses the regional energy mix potentials of Japan for maximised renewable electricity generation and reduced $CO_2$ emission intensity in the electricity sector, in view of the nationally determined contribution (NDC) mitigation target, and the 2 °C rise limit target. Beginning with the deregulation of the retail electricity market, discussions have been initiated about Japanese electricity system reforms towards 2020. This paper examines the potential energy mix up to 2030 at the regional level, and identifies the need to accelerate electricity system reforms to expand the transregional access to renewable electricity generation. By analysing available data, we assess how regional renewable energy potentials can be put to effective use, and identify how electricity reform should proceed, to both capitalise on renewables and reduce carbon intensity. Finally, we report the large renewable potentials in Japan. However, in order to maximise the use of these potentials, a combination of technologies and policies are required to promote flexible grid operation, and strengthen transmission capacity and renewable priority dispatch order, as well as to introduce technology for stabilizing electricity systems supplied by renewable electricity, such as pumped storage hydropower, storage cells, and demand-response, which can store surplus energy until it is needed.

## 1. Introduction

The Fukushima nuclear accident in 2011 starkly brought the inability to transmit electricity between regions within Japan into light. Much discussion has since transpired on reforming the electricity market and various energy related policies, including the feed-in tariff (FIT) (Huenteler et al., 2012; METI, 2013a, 2013b). The goal of the reform is to legally decouple electrical power production from distribution and transmission by 2020. On the other hand, in the 2016 Japan-ratified Paris Agreement to keep the global temperature rise to below 2 °C,[1] to put forward their best efforts through nationally determined contributions (NDCs), and to strengthen these efforts. Under such circumstances, electricity market reform towards 2020 and beyond needs to factor in effective reduction in $CO_2$ emissions, as well as meeting the following three government objectives: secure a stable supply of electricity, suppress electricity rates, and provide greater choice for consumers through competition amongst business entities.[2] Furthermore, increasing a share of clean electricity in the energy mix of the overall electricity supply will bring about a large reduction in the national $CO_2$ emissions (Keay et al., 2012; NIES, 2010; DDPP, 2015).

This study assesses regional energy mix potentials of Japan, to maximise the power generation of renewable electricity potentials and reduce the $CO_2$ intensity of the electricity sector. We focus on renewables over nuclear energy in terms of reducing $CO_2$ emissions and increasing domestic energy security to reduce dependence on primary energy imports and uncertainties of economic, social and environmental impacts by nuclear power plants such as nuclear accidents, and to achieve the Japanese climate target. Although there are various discussions on nuclear power generation (Karakosta et al., 2013; Pfenninger and Keirstead, 2015; Roth and Jaramillo, 2017), uncertainties regarding cost and safety surround it. In fact, since the Fukushima nuclear accident, the government budget spending on nuclear power has dramatically increased due to the newly introduced budget for Nuclear Damage Compensation – which started from JPY 5027 billion in 2011 and rose to JPY 8852 billion in 2014 – in addition to the existing nuclear power generation related subsidies,[3] and there are still

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[1] Citied as "Paris Agreement requires all Parties to put forward their best efforts through 'nationally determined contributions' (NDCs) and to strengthen these efforts in the years ahead." http://unfccc.int/paris_agreement/items/9485.php.

[2] METI Energy Market Reform in Japan: http://www.enecho.meti.go.jp/en/category/electricity_and_gas/energy_system_reform/.

[3] The governmental budget data is available from Ministry of Finance (MoF) database: http://www.bb.mof.go.jp/hdocs/bxsselect.html.

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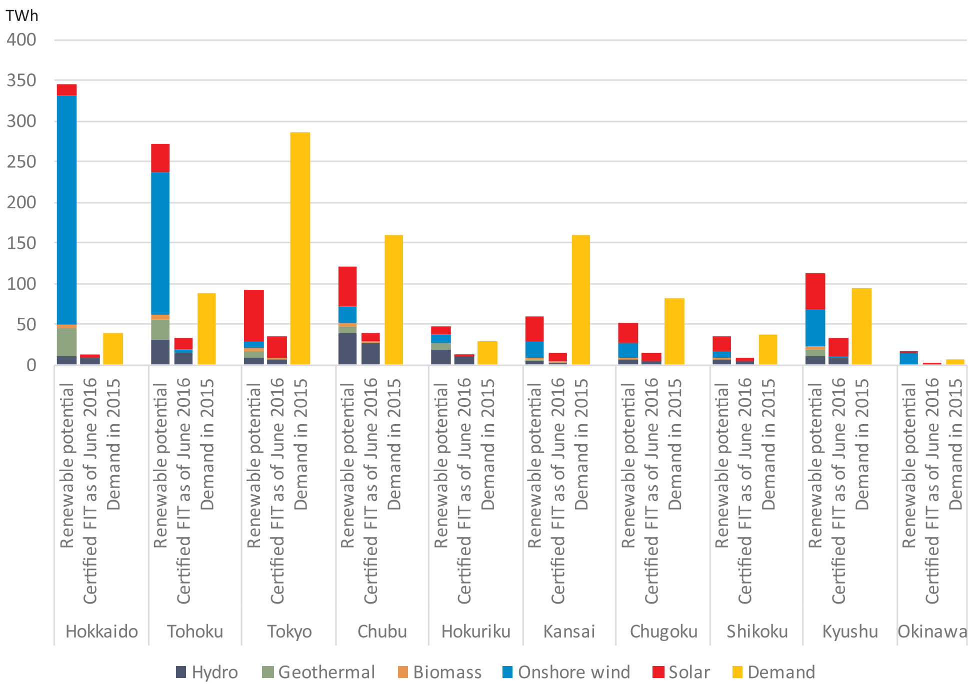



**Fig. 1.** Annual regional electricity potential, certified capacity, and demand by region.
Source: Made from the following sources: Renewable potentials, certified FIT (METI's FIT data) METI's FIT data: http://www.fit.go.jp/statistics/public_sp.html, Demand (METI's electricity demand and supply survey data) METI's electricity demand and supply survey data: http://www.enecho.meti.go.jp/statistics/electric_power/ep002/results_archive.html

issues to deal with regarding the disaster-related costs of nuclear power plants.[4] On the other hand, renewables could have the potential to increase local employment, facilitate local autonomy via decentralised power generation (Blazejczak et al., 2014; Vivoda, 2016), and could be more cost-effective than nuclear power (Sovacool, 2010), as it found that operation costs of nuclear power has been rising in countries such as Germany and the United States (Froggatt and Schneider, 2015).

This paper considers two scenarios based on the mitigation target of Japan as issued by government and determined by the NDC, called the "NDC scenario", and based on the target estimated by IEA 450 scenario for Japan to limit the global rise in temperature to below 2 °C, called the "2 °C scenario (2DS)". These two targets are rather top-down targets and not well examined regional details and from regional integration point of view. Regional differences exist in the regional electric power capacity, as well as the demand and supply structure in Japan. By looking closer at these variations, this paper highlights the gap between the estimated electricity supply and demand in these regions, to identify both the transmission capacity, and the challenges in expanding renewables. It also highlights the barriers in transmitting electricity from regions with large renewable potential to other regions. The findings from the analysis are intended to help shape the electricity system reform due to take place in 2020.

The paper is structured as follows: the next section covers the current structure of the electricity system in Japan, and the challenges involved with it; section three explains the methodology for the study; section four introduces spreadsheet data analysis to assess the regional energy mix; section five addresses recent discussions surrounding the electricity market reform towards 2020, and the feasibility of such reforms based on the regional electricity mix anticipated for 2030. Finally, it concludes with a summary of the main points and policy implications of reforming the electricity market of Japan.

[4] Reuters, 9 December 2016, "Japan nearly doubles Fukushima disaster-related cost to $188 billion": https://www.reuters.com/article/us-tepco-fukushima-costs/japan-nearly-doubles-fukushima-disaster-related-cost-to-188-billion-idUSKBN13Y047.

## 2. Background and literature review

### 2.1. Renewable potentials in Japan

After the Fukushima nuclear accident, it became clear that there was a need to expand renewable energy as an alternative electricity source (EEC, 2012; Huenteler et al., 2012; Muhammad-Sukki et al., 2014). This resulted in the introduction of the FIT scheme in July 2012, after which Japan has had a marked increase of up to 30.7 GW in solar PV capacity, and the total renewable electricity installed capacity is 32.2 GW including other renewables, between July 2012 and September 2016. If certified FIT is included, the total generation from renewable sources approaches 120.8 GW excluding large hydropower. Here, certified FIT means all of the approved capacities of renewables as calculated by applicants (individual electricity producers or electricity businesses) who plan to install renewable electricity, and who have obtained FIT approval from the Ministry of Economy, Trade and Industry (METI), and electricity companies, although are yet to begin installed.[5]

In Japan, while disparities in power capacity exist among the regions, they are more pronounced in the renewable potential (Wakeyama and Ehara, 2011; Wakiyama and Kuriyama, 2015) – Hokkaido and Tohoku have huge renewable power surpluses and less power demands, however, the Tokyo, Chubu, and Kansai regions have high power demands (Fig. 1).

[5] Although equipment such as solar panels are not necessarily purchased at this approval level, documents on manufacturers and model numbers of such equipment to be installed need to be registered. Prior to April 2015, when regulations changed, approval from a regional electricity company to connect generated renewables to its grid was not required. Furthermore, for solar PV, a certified copy of land registration and a legal installation procedure status report for the site were not required, and there was no regulation then from approval to installation. Since April 2015, all renewable electricity producers need approval, not only from the government, but also from electricity companies to connect their produced electricity to the grid. In addition, solar PV electricity producers of more than 50 kW installed capacity need to submit a certified copy of land registration, legal procedure status report of the installation site, and equipment procurement documents within 180 days (maximum extended days is 360 days), otherwise they face expiry of the registered 'approved capacity' and obtained procurement price. Since "certified FIT" is registered in the FIT system and requires government approval, the relevant data are collected by the government. See the following METI site for information on the FIT (METI FIT database:http://www.enecho.meti.go.jp/category/saving_and_new/saiene/kaitori/nintei_setsubi.html).

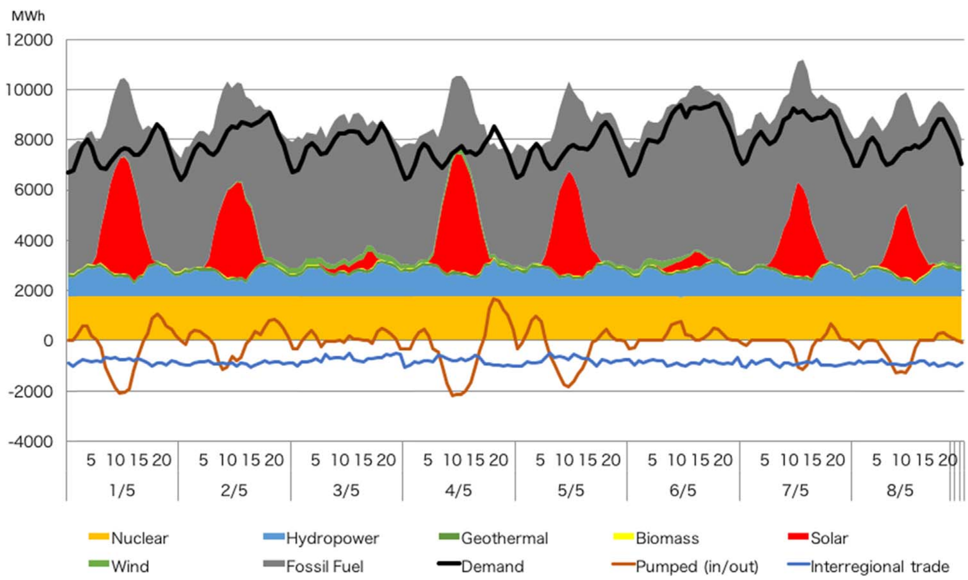



**Fig. 2.** Hourly electricity demand and supply from 1st May to 8 May 2016 in Kyushu.
Sources: Made from the following source: Kyusyu electricity power company electricity demand and supply data Kyusyu electricity power company electricity demand and supply data: http://www.kyuden.co.jp/wheeling_disclosure.html

According to the electricity power generation report published by the regional electricity companies from April to December 2016,[6] fossil fuels remain the primary source of electricity (70–90%) in all regions except Kyushu. For example, areas like Hokkaido and Tohoku, which have renewable potentials as shown in Fig. 1, yet largely rely on fossil fuels (80–85%), and only minimally on renewables (6–7%, excluding hydropower) over the same period. On the other hand, when the regional energy mix, and supply and demand curves on the daily level are considered, 55% and 40% of the total electricity supply peaks on 4th May at 11:00 in Hokkaido and Tohoku, respectively. In Kyushu, the share of fossil fuel power generation on that day is about 35%, and the solar power generation reaches 24% (Fig. 2). At peak, solar power covers 61% of the total electricity supply between 11:00 and 13:00 on 4th May, while dropping to 0% between 19:00 and 23:00. This shows that some regions have more renewable potentials than currently generated. However, in the current electricity system, Japan faces difficulties in expanding renewable generation (Kuwahara, 2015; Wakeyama, 2016), one of which is the current regional electricity system, and grid capacity.

### 2.2. Conventional regional electricity system and challenges for renewable energy expansion

The conventional electricity system in Japan, which comprises supply and distribution, has been dominated by ten regional companies – Hokkaido, Hokuriku, Tohoku, Tokyo, Chubu, Shikoku, Kansai, Chugoku, Kyushu, and Okinawa Electricity Power Companies[7] (Fig. 3) – each of which is responsible for supplying electricity and operating electricity systems within its geographical region. However, the conventional system contains a fatal flaw, which was exposed by the Fukushima nuclear accident following the Great East Japan Earthquake: the inability to trade electricity between regions (METI, 2013a, 2013b). Under the system of regional monopolies, electricity could not be flexibly transmitted to regions where it was needed most, the Tokyo region in this case, and as a result, Tokyo was faced with acute supply shortages (Vivoda, 2012; Aoyama, 2017; METI, 2017). Part of the problem lies in a long-standing vertically integrated utility, where the power plant, transmission grid, and distribution are all owned by each of the 10 regional electricity utility companies, the constraints of which Japan started to address in 2013. Moreover, current transmission capacities between regions are limited. Increasing the capacity of the interconnections between Hokkaido and Tohoku is key to realising increased use of renewable electricity in Japan: a large renewable potential exists in Hokkaido, from where surplus power needs to be transmitted to the Tokyo region through Tohoku. Although the interconnection grid is planned to expand from 0.6 to 0.9 GW by March 2019 (METI, 2015b), this capacity is still insufficient to support the transmission load that could result if the wind power potential of Hokkaido is fully realised.

In addition, this regional monopoly has been a barrier to trading renewables between regions. The transmission capacity between control zones is limited and inflexible, and there is insufficient grid capacity for new energy sources, such as renewables (Wakeyama, 2016). Prior to reform of the electricity market, electricity companies operated grid interconnections, and balanced energy demand and supply to stabilise electricity supply based on the most economical energy mix (ETRA, 2014; FEPC, 2015a). In the electricity market reform, being initiated by a METI-led market system reform committee (METI, 2017), the cross-regional electricity trade is expected to be structured to increase flexibility. Starting 2015, regional interconnection of grid use is to be controlled by the newly established Organisation for Cross-regional Coordination of Transmission Operators (OCCTO) (OCCTO, 2017).

Moreover, currently discussed as part of the reform is a restructuring of the ‘first-come-first-served rule to avoid meaningless competition’, as well as ways to enhance grid facilities and expand grid use. The ‘first-come-first-served rule’ is used to allocate the grid transmission capacity, where maximum output capacity in kilowatts is registered up to 10 years ahead, and in principle, the capacity registration is carried out on a first-come-first-served basis[8] (Wakeyama, 2016).

[6] OCCT website: http://occtonet.occto.or.jp/public/dfw/RP11/OCCTO/SD/LOGIN_login#.

[7] The ten power companies oversee regional power supply services as general electrical utilities, and are responsible for supplying electricity from power generation to distribution to the consumers in their respective service areas (FEPC, 2015a). General electrical utilities supply about 84% of the demand, and sell 96% of electricity in Japan as of 2014. As a first step towards electricity market reform, the liberalisation of the electricity retail market started from 2016. However, 66% of electricity is yet generated, and 92% sold by these ten electricity companies as of June 2016. (METI electricity research and statistics database: http://www.enecho.meti.go.jp/statistics/electric_power/ep002/results.html#headline2).

[8] Mid-term report of committee of Regional Interconnection Transmission Grip Capacity Rules (2017) (Japanese). Organisation for Cross-regional Coordination of Transmission Operators. (https://www.occto.or.jp/iinkai/renkeisenriyou/2016/files/renkeisen_kentoukai_07_04-1.pdf).

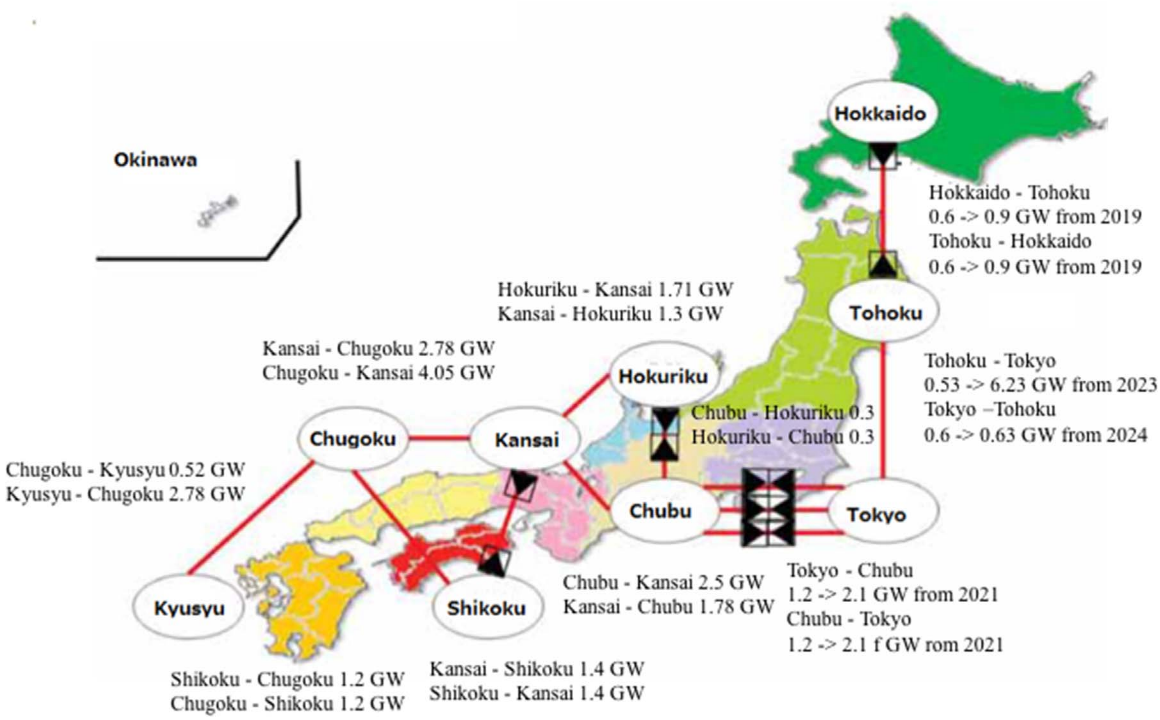



**Fig. 3.** Map of current and planned grid interconnection capacity.
Source: (METI, 2012), OCCTO (2017) OCCTO: Calculation method and result of operating capacity of each interconnection line https://www.occto.or.jp/renkeisenriyou/oshirase/2016/files/sankou_h28_bessatu.pdf. The numbers shown between Hokkaido-Tohoku, Tokyo-Chubu, and Kansai-Shikoku are the current and planned transmission capacity including heat capacity (GW) that are categorised as maximum transmission capacity that can be operated without any technical constraints. The number between other regions do not have any plans for expanding the transmission grid capacity up to 2026. Therefore, the number indicates maximum transmission capacity including heat capacity, safety operation, stabilising voltage, or/and maintaining frequency of operation.

Under this old rule, what really happening is that the planned transmission is allocated and occupied largely by 'planned power generation' especially fossil fuels and nuclear power capacity, which hinders already FIT registered renewables in utilizing the grids. Restructuring of the 'first-come-first-served rule' can increase the efficiency of the priority mechanism in the real-time market (Bahar, 2013). For instance, under the conventional system, if the cross-regional grid capacity exceeds the maximum transmission capacity, market segmentation occurs, which results in electricity not being tradable across regions; flexibility is therefore needed in cross-regional trade to avoid such market segmentation (Neuhoff et al., 2015). The current discussion in Japan is to shift the grid use from 'first-come-first-served" to "indirect auction," which would increase liquidity in the cross-regional electricity trade through the spot market (METI, 2017).

The challenges in the expansion of renewable electricity is not only the capacity for cross-regional trade, and connections to the existing regional grid system, but also the capacity that can be connected to the grid within a region (Wakiyama and Kuriyama, 2015).

The "priority dispatch order" of the electricity supply within a region is premised on avoiding curtailment of long-term electricity generation contracts between electricity generators and distribution companies,[9,10] (Wakeyama, 2016). Such long-term generation contracts include nuclear, hydropower, and geothermal, as defined under the guidelines of transmission and distribution by the OCCTO.[11] The fact that the long-term contracts include nuclear means that nuclear has priority over solar and wind power generation. Regional power companies were not obligated to give priority access to renewable energy, or to expand the interregional grid in the advent of grid overloads or bottlenecks (Jones Day, 2013; Ichinosawa et al., 2016). However, while the long-term contracts are for maintaining a long term stable supply of electricity, it alone does not necessarily determine the electricity price, or change the market value of electricity generation assets (Wilson et al., 2005). Regarding the stabilisation of electricity supply over the long term, the level of reliability depends on how much capacity consumers are willing to commit to for long-term contracts, and how much they are willing to pay for security of supply (Vázquez et al., 2002).

In terms of the accessibility of renewables into the grid system within a region, the Japanese government set up the priority dispatch rule in 2011 to give renewables priority to be purchased and connected to the grid.[12] However, although the priority dispatch rule defines the order of priority of renewable generation (solar and wind power generation) after long-term fixed electricity supply, and provides an assurance that solar and wind power can be connected to the grid second in priority after long-term sources like nuclear and hydropower generation,[13] it also defines an exception for securing a smooth supply of electricity in the event it is disturbed (GOJ, 2011).

As shown in Fig. 2, in Kyushu area, renewable power generation already contributes to more than half of the electricity supply, while nuclear comprises only 0.2%. According to the Kyushu Electricity Power Company, nearly half of the total electricity supply (44%) is expected to be supplied by nuclear once all the nuclear generators have

[9] METI 2015 (Japanese): http://www.meti.go.jp/committee/sougouenergy/kihonseisaku/denryoku_system/seido_sekkei_wg/pdf/012_06_04.pdf.

[10] Kyusyu Electricity Power Company 2016 (Japanese): https://www.kyuden.co.jp/var/rev0/0055/4202/ob3v76j5.pdf.

[11] OCCC 2016 (Japanese): https://www.occto.or.jp/jigyosha/koikirules/files/shishin161018.pdf.

[12] The electricity demand as of 2015 was 79 TWh while the estimated nuclear power generation 34 TWh (Kyusyu EPCO: http://www.kyuden.co.jp/var/rev0/0060/2611/uaou4h43gw7.pdfKyusyu EPCO data book: http://www.kyuden.co.jp/var/rev0/0067/8083/data_book_2016_all_h.pdf.

[13] METI 2015 (Japanese): http://www.meti.go.jp/committee/sougouenergy/shoene_shinene/shin_ene/keitou_wg/pdf/006_01_00.pdf.

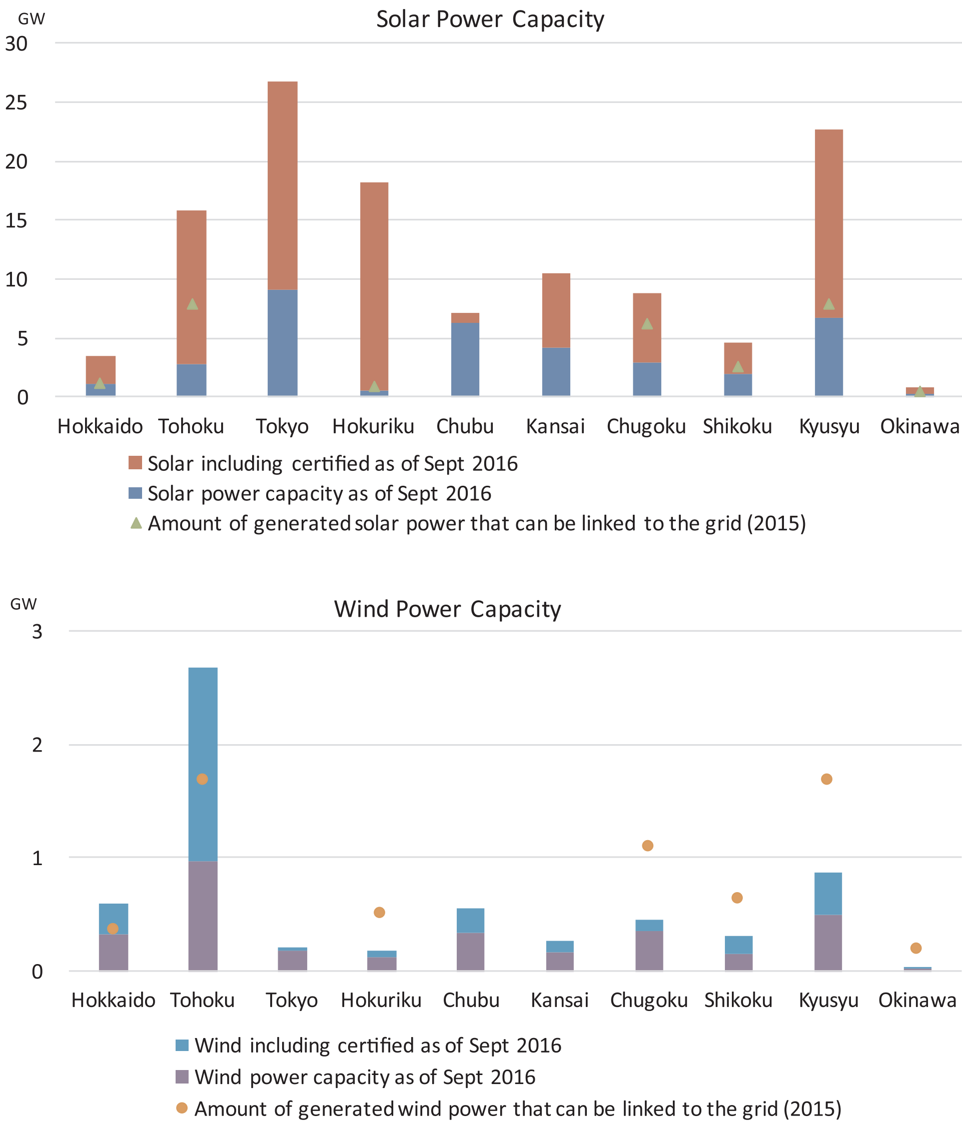



**Fig. 4.** Solar and wind power capacity in 2016 and grid capacity approved by regional electricity companies to access to grid in 2015.
Sources: Made from the following source: FIT data from METI METI's FIT data (Japanese): http://www.fit.go.jp/statistics/public_sp.html. "Certified" means all of the approved capacities of renewables as calculated by applicants (individual electricity producers or electricity businesses) who plan to install renewable electricity, and who have obtained FIT approval from the Ministry of Economy, Trade and Industry (METI), and electricity companies, although are yet to begin generation. Tokyo, Kansai, and Chubu regional electricity companies does not set maximum capacities (amount of generated wind power that can be linked to the grid) for solar and wind. For solar PV, as of September 2016.

restarted operation.[12] This is one of the reasons the capacity limit of renewables to access the grid has already reached the maximum limit in case of solar PV. Under such circumstances, in 2014, owing to the likely risk of blackout from overload, regional power companies set up rules for capping the capacity of electricity generated from solar and wind that could be connected to the grid,[13] and suspended purchasing renewables under the FIT system and transmit renewables on its grid, presenting yet another challenge for the expansion of renewables.[14] Since then, regional electricity companies have been required to estimate how much power can be linked to the grid by electricity sources based on the demand and supply balance.[15] Fig. 4 shows the limits of handling capacity of the regional grid system for solar and wind as of 2015 by comparing the installed capacities, and the capacity including certified FIT[16] of solar and wind power as of September 2016. Each electricity company, except for Tokyo, Kansai, and Chubu, has set maximum capacities for solar and wind. For solar PV, as of September 2016, Tohoku, Hokuriku, and Okinawa were already at maximum capacity (Fig. 4). If solar PV including certified FIT is counted, almost all regional electricity power companies have already exceeded maximum capacity. For wind power, the capacities including certified FIT in Hokkaido and Tohoku have already reached maximum (Fig. 4). Therefore, all expected available solar and wind renewable power cannot connect to the grid. As such, despite the increase in renewable electricity potential in Japan made available by the introduction of the FIT system in 2012, more challenges to the further expansion of renewables within and between regions exist.

### 2.3. Scope of this paper

A substantial number of studies have evaluated, based on the supply and demand optimisation model, the extent to which renewable resources could potentially and systematically be integrated into the power grid of Japan, using technical measures for intermittency, such as rechargeable batteries, and suppression control of surplus electricity from the renewable system (Komiyama and Fujii, 2014; Inoue et al., 2017; Tsuchiya, 2012; Ogimoto et al., 2014). However, such studies have not assessed the renewable potentials and energy mix at the regional level based on the NDC and 2 degrees target of Japan, or deal with certain issues raised by the 2020 electricity market reform currently under discussion. So, our first issue to tackle

[14] Kyusyu Electricity Power Company (Japanese): http://www.kyuden.co.jp/var/rev0/0043/8137/ai4p5cx3.pdf.

[15] METI 2015 (Japanese): http://www.meti.go.jp/committee/sougouenergy/shoene_shinene/shin_ene/keitou_wg/pdf/006_01_00.pdf.

[16] Under the current FIT system, electricity companies are obligated to accept the supply and purchase of electricity generated from renewables, upon request from parties planning to supply renewable energy generated by a power plant certified by METI, and power companies (hereinafter such power facilities are called 'certified capacity'). Certified capacity is not yet installed.

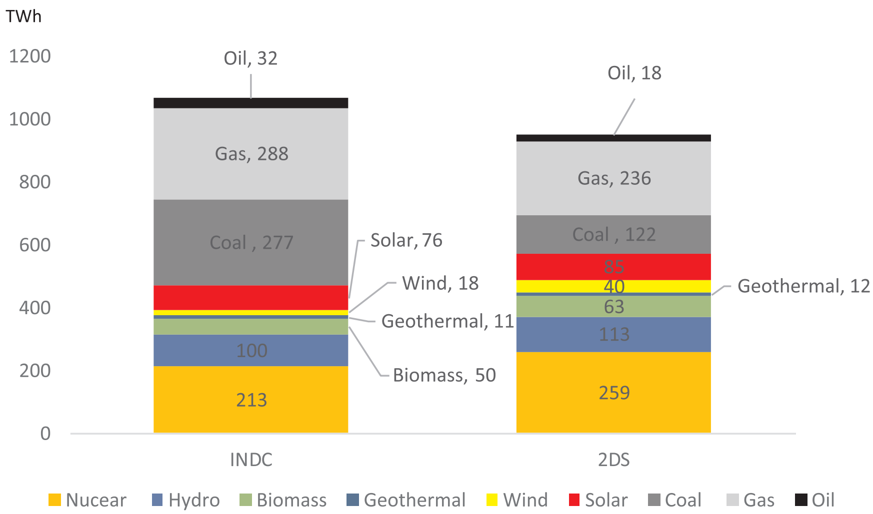



**Fig. 5.** Energy mix of Japan's NDC and IEA 2DS in 2030.
Sources: Made from data from the following sources: IEA (2015); UNFCCC (2015)

here is precise examination of renewable potentials region by region. In addition, while these studies are aimed at estimating storage capacity based on simulations, the scenarios in this paper examine the capacity of the interconnection grids. We pay attention to the potential electrical power generation of each power source by 2030 by considering the planned transmission network capacity by 2030, without the first-come-first-served rule. It highlights the barriers in transmitting electricity from regions with large renewable potential to other regions under the conventional transmission system, even though some barriers can be overcome. Although the conventional electricity supply system has changed since April 2016 with the deregulation of the retail electricity market, 92% of the electricity is still distributed via ten regional electricity companies as of March 2017.[17] Thus, this paper analyses electricity generation capacity based on the boundaries of the ten regions.

Considering the issues described in Sections 2.1 and 2.2, this study estimates the supply and demand balance whilst allowing for gaps in hourly power generation in the regions by applying data from Japan's NDC[18] and the International Energy Agency (IEA) 450 scenario[19] (here, called the "2 °C scenario (2DS)") to the demand and supply curve based on a scenario in which renewables have priority dispatch to the grid by 2030. It also identifies whether renewable electricity potentials can meet the regional electricity demand, and whether the surplus renewable electricity generated in a region can be transmitted across regions; that is examined based on the current discussion over the electricity market reform in Japan.

## 3. Methodology

As described in Section 1, this study aims to examine, to achieve the government climate target (NDC) and the IEA 2 degrees target, how much renewable energy potential exists, and how the carbon intensity of electricity can be improved by 2030. It is assessed by looking at nationwide aggregated management, flexible priority criteria, and precise hourly control that is applied to the electricity system by introducing the planned transmission capacity by 2030, and electricity system reform where electricity transmission across the regions can be traded by reforming the current 'first-come-first-served grid transmission rule'. To test the feasibility of the electricity market reform as currently discussed by the government, we examine the regional energy mix in 2030 using two scenarios – the NDC and the 2DS as set by IEA 450 scenario. By estimating the power generation in 2030, the supply and demand structure of regional electricity are revealed, and the kind of electricity market anticipated to be in place by 2030 is identified.

Potential electricity supply is estimated by considering the hourly fluctuation in electricity demand and supply from renewable sources for each region, i.e., Hokkaido, Tohoku, Tokyo, Chubu, Hokuriku, Kansai, Chugoku, Shikoku, Kyushu, and Okinawa. To investigate how each electricity system can satisfy fluctuating electricity demand with an intermittent renewable electricity supply, we develop electricity demand and supply curves for each electricity source. Using a spreadsheet model, hourly electricity demand and supply data are fed into the spreadsheet to analyse the energy mix and determine the electricity supply sources on an hourly basis. The hourly electricity demand and supply curve, as of 2014, for the total demand and supply, adjusted for total electricity demand and supply anticipated in 2030 in accordance with Japan's NDC target level, was used in the calculations. For the 2DS, the same methodology as for the NDC is used, based on data from the IEA 450 scenario for Japan. For electricity supplied by solar and wind power, hourly basis curves are created using data from 1300 points throughout Japan fed into the Automated Meteorological Data Acquisition System (AMeDAS), made available via the Japan Meteorological Agency website. From AMeDAS, we used data from around 50 solar radiation stations and 484 wind speed stations located in potential wind power sites. The procedure is described in detail in Appendix A (Appendix A shows the algorithm used for this calculation, and an example of hourly output of electricity system analysis). This is a common method for the demand and supply curve simulation model (Komiyama and Fujii, 2017; Inoue et al., 2017; Tsuchiya, 2012). Geothermal and hydropower are used as the fixed electricity baseload.

To examine the regional grid capacity of Japan for renewables in 2030, which considers the current discussions of electricity market reform, the following current electricity priority dispatch order without capping the capacity of electricity generated from solar and wind is used to estimate the essential electricity supply required to meet the demand in each regional electricity system in 2030 (the long-term fixed baseload electricity – renewables – biomass – interconnection trade – fossil fuel power generation): the first is to estimate the long-term fixed baseload electricity, i.e., nuclear power, hydropower, and geothermal power, in each region; the second is to estimate electricity from solar and wind power generation in each region; the third is to estimate the power from biomass; the fourth is pumped hydropower plants[20]; and the last is power from the amount of fossil fuel power generation needed for the peak load or balancing demand and supply.

[17] METI electricity database: http://www.enecho.meti.go.jp/statistics/electric_power/ep002/results_archive.html.

[18] Japanese NDC: http://www4.unfccc.int/submissions/INDC/Published%20Documents/Japan/1/20150717_Japan%27 s%20INDC.pdf.

[19] In IEA WEO 2015, 450 S refers to "a pathway to the 2 °C climate goal that can be achieved by fostering technologies that are close to becoming available at commercial scale".

[20] Under the current priority dispatch order, pumped hydropower plants come after fossil fuels, but this paper prioritises it over fossil fuels as a function of energy storage for renewables.

This paper also compares the energy mix with and without nuclear power for the NDC and 2DS. Although nuclear power is considered as the first dispatch priority under the current electricity market and anticipated electricity market reform in Japan, currently, only Kyushu and Shikoku power companies generate electricity from nuclear, with amounts of 1.3 TWh and 0.6 TWh, respectively, as of September 2016.[21] Under Japan's NDC, nuclear is anticipated to account for 213 TWh, which illustrates the uncertainty surrounding restarting the use of nuclear on a nationwide basis by 2030. This issue will be described in detail in the next sub-section. Furthermore, if nuclear were to fulfil the regional capacity, it would act as competition for renewables; thus, this paper also reports estimates of a zero-nuclear scenario in 2030.

### 3.1. Input data

The primary effort in input data creation is how to allocate the national level amount of power decided in the NDC and IEA 2DS into the ten regions. Thus, we allocate electricity at the regional level in this section using existing data. For the energy mix in 2030, as Japan's NDC and IEA 2DS are targeted at the national level (Fig. 5), no details exist for the regional level. This study, therefore, breaks down the national energy mix target into regional targets by technology as follows.

To estimate the possible energy allocation to achieve the 2030 target, we allocated the electrical power sources in the following order. First, we estimated the potentials of renewable power generation at the regional level using certified FIT renewable capacity reported by METI. Renewables such as wind and geothermal require several years to be certified for FIT. Therefore, we also used other methods to calculate regional renewable potentials for large hydroelectric, geothermal, and wind power. Next, the feasible nuclear power capacity was estimated using data from each nuclear plant that is owned by regional electricity utilities and wholesale electricity utilities, and distributed by the regional electricity companies. Finally, we estimated fossil fuel power generation to meet electricity demands.

The detail regional allocation and estimation of potential of hydroelectric, geothermal, wind, solar, and biomass power generation are described as the following. Firstly, in the case of large hydroelectric power generation data at the regional level, we used the METI hydropower database[22] as it provides data at the prefectural level, and used the FIT database for small-middle hydropower generation published by METI.[23] Hydropower generation in 2015, which includes large and middle-small hydropower generation, is 93 TWh,[24] and rises to 99 TWh if the certified FIT installed capacity as of July 2015 of middle-small hydropower generation is added, which is approximately the NDC figure of 98 TWh. Thus, the regional share of hydropower generation is used to adjust the total power generation to meet the NDC figure. For the 2DS, we used the FIT data, including the certified FIT data as of September 2016 of 101.3 TWh. Because hydropower generation of the 2DS by 2030 is 113 TWh, we used a share of the FIT data to meet 113 TWh.

Secondly, for the geothermal power generation capacity at the regional level,[25] we used the data obtained from the Japan Oil, Gas and Metals National Corporation (JOGMNC),[26] as well as the company announcements of plans for public consultation to develop geothermal power plants,[27] and then calculated the expected total installed capacity of geothermal power for 2030. Based on this, the feasible geothermal power generation by 2030 is estimated at 10 TWh[28,29]. Japan's NDC is 12 TWh for geothermal power generation by 2030; thus, this paper adjusts the geothermal power generation to 12 TWh using a share of the regional capacity with an estimated 10 TWh regional capacity. Geothermal power generation under the 2DS is the same as the figure for the NDC (i.e., 12 TWh).

Thirdly, for wind power generation, this study uses the installed capacity from FIT data, which results in installed capacities of 13.6 TWh and 15.4 TWh for July 2015 and September 2016,[30] including FIT-certified capacity. Japan's NDC targets 18 TWh of wind power generation by 2030; therefore, to estimate the regional wind power generation by 2030 we used a share of the wind power generation from the FIT data, including certified FIT by region, and adjusted the power generation to obtain 18 TWh in total. Wind power data estimated from METI (2011) reports are used for wind power generation under the 2DS. Additionally considered was the project internal rate of return (PIRR)[31] of potential renewable electricity at the regional level. Wind power generation was based on an 8% PIRR after tax, and a willingness to install wind power under an assumed FIT system. The analysis results indicated 43 TWh of onshore wind power generation, which is approximately the 2DS expected wind power generation of 40 TWh. Thus, we used the ratio of regional wind power capacity estimated in the METI reports to the 2DS power generation target.

In addition, for solar power generation, 33 TWh has already been installed, and the certified FIT solar power in 2015 is 103 TWh (144 TWh as of September 2016). The NDC and IEA 2DS targets are at 79 TWh and 85 TWh, respectively, which will be well covered by 136 TWh (33 TWh plus 103 TWh). Thus, we considered the share of solar power as of July 2015.

This study aims to identify barriers to the current electricity system when the NDC and 2DS renewables targets are achieved. Therefore, we used the targeted total power generation for solar and wind by the NDC and 2DS for the analysis. The surplus solar and wind power capacity in hourly electricity supply basis can be used to replace fossil fuels.

Similarly, for biomass power generation, while Japan's NDC for biomass is 49 TWh, the FIT power generation estimated from the installed capacity is 27.5 TWh as of July 2015 and 38 TWh as of September 2016[32,33]. We thus take the share of regional biomass power generation as of September 2016 and estimate the power generation of

[21] http://www.enecho.meti.go.jp/statistics/electric_power/ep002/results.html.

[22] Hydropower generation data extracted from METI: http://www.enecho.meti.go.jp/category/electricity_and_gas/electric/hydroelectric/database/energy_japan001/.

[23] This paper uses FIT data from METI: http://www.fit.go.jp/statistics/public_sp.html.

[24] Small- and medium-sized hydropower plants is estimated to have a fixed capacity factor of 60%, which was used (as published by MOE, 2013) to estimate small-medium hydropower generation (TWh) from the installed capacity (kW).

[25] In the case of geothermal projects, it takes more than ten years to move from the initial ground investigation to the start of actual operations: two years for the ground and excavation investigation, three years for exploration, three to four years for the environmental assessment, and three to four years for excavation of the production well and construction (METI, 2015a). Obtaining FIT approval for geothermal projects requires environmental assessments, among other procedures. Furthermore, if public discussion and coordination with local communities are needed, another five years may be required, meaning that a project designed to begin operation in 2030 should begin public consultations today; although this assumption may be too conservative.

[26] Japan Oil, Gas and Metals National Corporation (JOGMNC) http://geothermal.jogmec.go.jp/.

[27] There is no information on the anticipated installed capacity of geothermal power plants in public consultations, thus this study assumes sites located in hot spring areas at 500 kW (minimum installed capacity of medium-scale geothermal); those in national parks at 30,000 kW (large-scale geothermal is more than 15,000 kW); and others at 2000 kW (maximum installed capacity of medium-scale geothermal). The data are based on a JOGMEC report (JOGMEC, 2013).

[28] Includes sites in national parks. In October 2015, MOE announced eased regulations for parts of national parks, meaning development of geothermal power generation is possible for some sites (source: Asahi Shimbun newspaper (6 October 2015): http://www.asahi.com/articles/ASH7Z46TVH7ZULBJ005.html).

[29] For geothermal electricity generation, we used a 70% capacity factor for installations of less than 5000 kW, 75% for installations of 5000–20,000 kW, and 80% for installations of more than 20,000 kW. Data from MOE (2013).

[30] We used the capacity factor of average wind speed due to factor variations of 16.2–54% in speed (in metres per second), and 2000 kW to 5000 kW in capacity (METI, 2011).

[31] PIRR is used to evaluate whether a project can be feasibly operated, and to determine whether the project will be successful or not. If PIRR is larger than the weighted average cost of capital (WACC), operation is usually feasible, with an expected return on investment. For instance, WACC is about 4.7–7.5% for onshore wind, and about 6.8–9.7% for offshore wind in some European countries and the USA (IEA, 2011).

[32] A fixed capacity factor of 80% is used for biomass, as published by METI (2013b), to estimate the biomass electricity generation (TWh) from the installed capacity (kW).

[33] The available biomass data published by NEDO is also 38 TWh in the total. http://app1.infoc.nedo.go.jp/biomass/index.html.

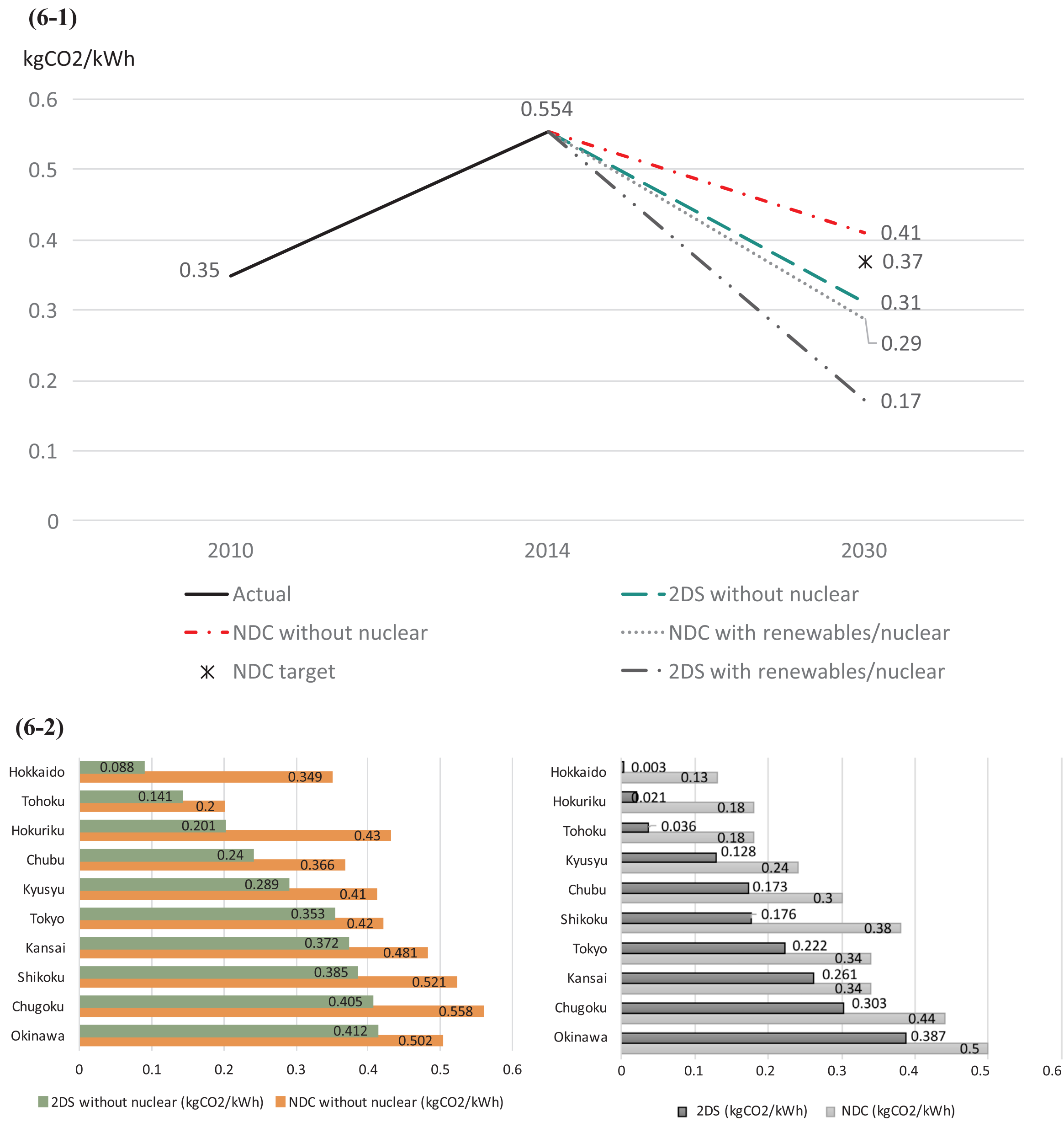



**Fig. 6.** (6-1) Estimated result of aggregated carbon intensity in national level using demand and supply curve. (6-2) Estimated result of carbon intensity by region using demand and supply curve. Figs. 6–1 and 6–2 shows the results of the calculated carbon intensity in 2030, which was estimated considering nationwide aggregated management, flexible priority criteria, and hourly precise control that is applied to the electricity system as a whole by introducing planned transmission capacity towards 2030, and electricity system reform where the electricity can be traded across regions by reforming the current 'first-come-first-served' grid transmission rule. Comparing with the NDC and the 2DS targets show that Japan can achieve the targeted carbon intensity if Japan reforms the electricity market to enhance aggregated management, and introduce flexibility in the priority criteria, and in transmission between regions.
Sources: Made from the following sources: *FEPC 2015 for actual national carbon intensity in 2010 and 2014, and the result of this paper*

49 TWh by region. For the 2DS, biomass generation is expected to be 63 TWh. In the absence of other data, we applied the share of regional biomass with the FIT power generation as of September 2016, and apply it to NDC.

Additionally, to estimate the regional nuclear power generation by 2030, we first listed all existing nuclear power plants,[34] then eliminated all plants that will have exceeded their 40-year operational lifespans by 2030, which leaves only 2.4 MW of generation capacity. Total power generation in the NDC and IEA are allocated to those remaining nuclear plants in each region. Yet, our detailed examination on plant operation rates, and uncertainty on lifespan of plants reveals that the NDC and IEA 2DS nuclear targets will not be reachable. Hence, we used a more realistic national target in the case of nuclear power. Even using a high capacity factor of 90% for nuclear, only 191.5 TWh could be generated, which falls short of Japan's NDC power generation target. The Nuclear Reactor Regulation Law was amended in 2012 after the Fukushima nuclear accident, where, in principle, the maximum operational lifespan of nuclear reactors was set to 40 years (Nawata, 2016). However, the regulation also set up an exception to expand by additional 20 years with the approval of the Nuclear Regulation Authority (NRA) (NRA, 2017). We, therefore, included the capacity of nuclear power from plants that have exceeded their 40-year lifespan by 2030, which includes nuclear plants that have been restarted, reactors restarted after passing the NRA conformity check, and newly approved revised nuclear power plant reactor installation as of February 2017. The total power

[34] We use the data from METI (as of February 2019): http://www.enecho.meti.go.jp/category/electricity_and_gas/nuclear/001/pdf/001_02_001.pdf.

generation from nuclear will be 217 TWh, which is about the NDC target of 213 TWh.

However, that is the case when nuclear plants are operated with a capacity factor of 90%, which is unrealistic. The estimated capacity factor by regional electricity utilities is around 70–85%[35] (the average capacity factor of nuclear power generation from 1990 to 2010 was 73.7%, with the highest being 84.2% in 1998, and the lowest being 59.7% in 2003[36]). Therefore, for the NDC, we included plants that have not passed the NRA conformity check, or have not been approved for reactor installation, but NRA conformity checks are underway. Further, they will not exceed their 40-year lifespan by 2030. Therefore, nuclear power generation results in 214 TWh[37]– which is approximately the NDC target – with the capacity factors published by regional electrical power companies. Based on this data, we estimated the share of the regional nuclear power generation, and calculated the regional nuclear power generations by 2030. For the 2DS, we included all existing nuclear power plants that have not exceeded their 40-year lifespan by 2030. Thus, the total power generation from nuclear sources will be 285 TWh using the capacity factors published by the regional electricity power companies, which exceeds the 2DS target of 259 TWh. With the share of the regional nuclear power generation data, the expected total nuclear power generation of 259 TWh is allocated to regional nuclear electricity generations. These estimates reveal that the targeted nuclear power generation for the NDC and 2DS is unrealistic and unachievable. Thus, this paper reports alternative energy sources to nuclear, and consider the case of zero nuclear and to maximise the use of renewables within the targeted amount of renewable electricity to replace nuclear to meet the NDC and 2DS targets. It is because under the dispatch order where nuclear has first priority order, some of renewables cannot be used, and are wasted even if it is generated.

For fossil fuels, we used survey data of existing and planned fossil fuel plants at the regional level, as collected by the Ministry of Environment of Japan. To obtain regional figures for coal-fired, gas-fired, and oil-fired power generation that agree with Japan's NDC, we calculated the total power generation of fossil fuel power plants that will not have exceeded their 40-year lifetimes by 2030, as well as fossil fuel power plants planned to start operations before 2030, and then adjusted for the plant operation rate to meet the NDC and 2DS targets.

We also collected data on the interconnection grid capacity, and the capacity of pumped hydropower plants. For grid capacity, we used planned interconnection grid capacity data, including heat capacity by 2030. For pumped hydropower plants, we used the electricity supply data as of 2015 obtained from METI.[38]

## 4. Results

From the analysis, it reveals that Japan could reduce its carbon intensity from electricity generation to 0.29 $kgCO_2/kWh$ for the NDC (0.17 $kgCO_2/kWh$ for the 2DS), which improves from 0.55 $kgCO_2/kWh$ as of 2014 (Fig. 6–1), but it can be achieved if Japan meets the following requirements; renewables can be generated to the level of Japan's NDC target by 2030; renewable electricity is generated in based on the regional renewable capacity; fossil fuel power generation is used to balance the electricity demand and supply; and the available cross-regional transmission capacity can be maximised. In comparison, our analysis of the energy mix and carbon intensity is based on the aggregated use of renewables to meet Japan's NDC and 2DS targets. It also considers a priority dispatch order that the NDC target does not, which is as follows: baseload – renewables – biomass – interconnection trade – fossil fuel power generation. As a result of this analysis, we find that the new aggregated approach improves the carbon intensity of electricity more than the NDC target. The voluntary emission intensity target suggested by power companies is 0.37 kgCO2/kWh (FEPC, 2015b). The carbon intensity of 0.29 $kgCO_2/kWh$ can be achieved by replacing 20 TWh (NDC targets) of fossil fuels to renewables in balancing hourly electricity supply and demand without capping the capacity of electricity generated from solar and wind, and further reduction of the carbon intensity of 0.17 $kgCO_2/kWh$ can be achieved by replacing 26 TWh of fossil fuels to renewables.

The analysis also reveals that there is a huge reduction in emission intensity in Hokkaido, Tohoku, Hokuriku, and Kyushu – all of which meet the nuclear and renewable potential for 2030, but have relatively low electricity demand compared to other regions, especially highly populated areas like Tokyo. Comparing the carbon intensity targets in the NDC, the 2DS, and 2DS without nuclear reveals that aggregating renewable power generation to the 2DS level without nuclear will reduce Japan's carbon intensity to a level of 0.31 $kgCO_2/kWh$, which is below that stated in the NDC target by electricity companies (Fig. 6–2). Although the NDC without nuclear will exceed the carbon intensity that stated in the NDC target, this paper reveals that Japan can increase more renewables than the NDC target as described below, which will result in further reduction of carbon intensity from 0.41 $kgCO_2/kWh$ in the NDC target without nuclear. In the regional level, Hokkaido, Tohoku and Chubu area have potentials to reduce carbon intensity even in case of no nuclear. Hokkaido has relatively high carbon intensity in case without nuclear mainly because solar PV generation for the NDC target is estimated by the share of the installed capacity as of July 2015 when solar power in Hokkaido is still small compared to their solar PV potentials in the area.

The result of Japanese renewable potentials towards 2030 finds that enough renewable capacity exists to fulfil requirements of the current plan. As for the possibilities of increasing renewables to the level of the 2DS, if we consider the latest FIT renewable data, the power generation from renewables in Japan has already reached 147 TWh without large hydropower generation, as of February 2017.[39] Including both existing capacity and capacity under development, hydropower generation amounts to 241 TWh, which approaches the NDC target of 256 TWh of renewables by 2030, making up 24% of the total electricity generation. Furthermore, if certified FIT of renewables is included, it reaches about 300 TWh of renewables, which the 2DS target of 310 TWh for renewables. In addition, while solar PV in the 2DS expects 79 GW, the installed capacity of renewables including certified FIT as of February 2017 has already reached 121 GW.

On the other hand, although Hokkaido and Tohoku areas have large renewable potentials, these potentials are not factored into the 2030 targets under the current electricity market system. (Fig. 7) There are no incentives for investors to invest in these regions under a situation in which regional electricity power companies individually set caps for generation capacities for solar and wind power generation (SCJ, 2014). One of the challenges is the lack of power grid capacity. If new renewable potentials are introduced in the regional level, it exceeds their electricity demand within the region. Thus, the surplus power needs to

[35] METI 2016. http://www.meti.go.jp/committee/sougouenergy/shoene_shinene/shin_ene/keitou_wg/pdf/009_08_01.pdf.

[36] FEPC database in 2016 extracted from: http://www.fepc.or.jp/library/data/infobase/.

[37] For Hokkaido, Tohoku, Hokuriku, Chugoku, Shikoku and Kyusyu Electricity Power Companies, we use the data by METI 2016 (in Japanese) (the data is available: http://www.meti.go.jp/committee/sougouenergy/shoene_shinene/shin_ene/keitou_wg/pdf/009_08_01.pdf). For Tokyo, Chubu and Kansai Electricity Power Companies, the capacity factor is calculated by their historical capacity factors (Tokyo Electricity Power Company (EPCO): https://www4.tepco.co.jp/corporateinfo/illustrated/nuclear-power/nuclear-capacity-factor-j.html / Chubu EPCO: https://www.chuden.co.jp/energy/hamaoka/hama_jisseki/hama_setsubi/index.html?cid=ul_me / Kansai EPCO: http://www.kepco.co.jp/energy_supply/energy/nuclear_power/info/knic/library/unten/setubi.html).

[38] METI data: http://www.enecho.meti.go.jp/statistics/electric_power/ep002/results_archive.html.

[39] METI large hydropower database (http://www.enecho.meti.go.jp/category/electricity_and_gas/electric/hydroelectric/database/energy_japan006/).
METI FIT database (http://www.enecho.meti.go.jp/category/saving_and_new/saiene/statistics/index.html).

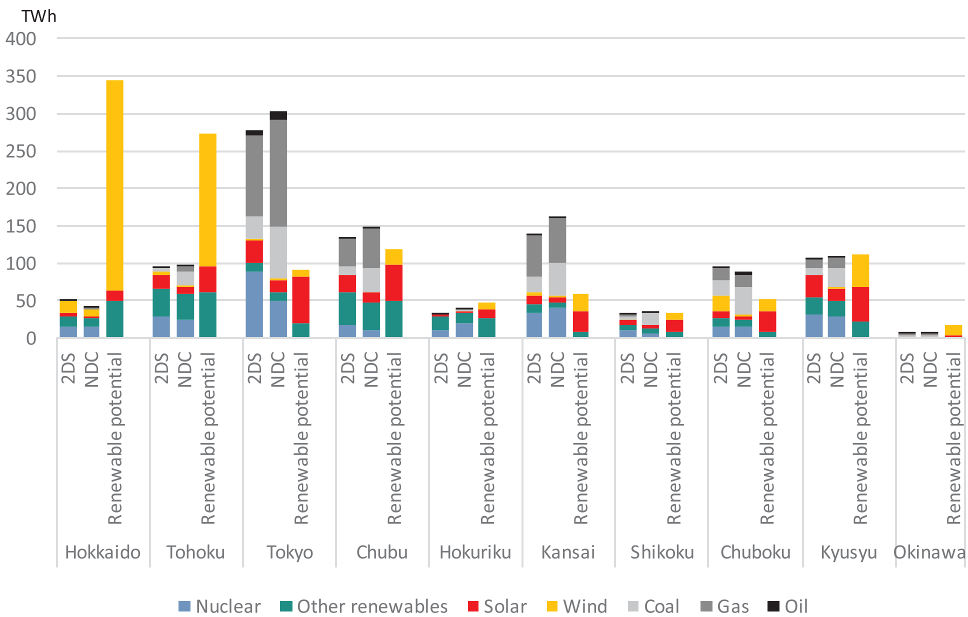
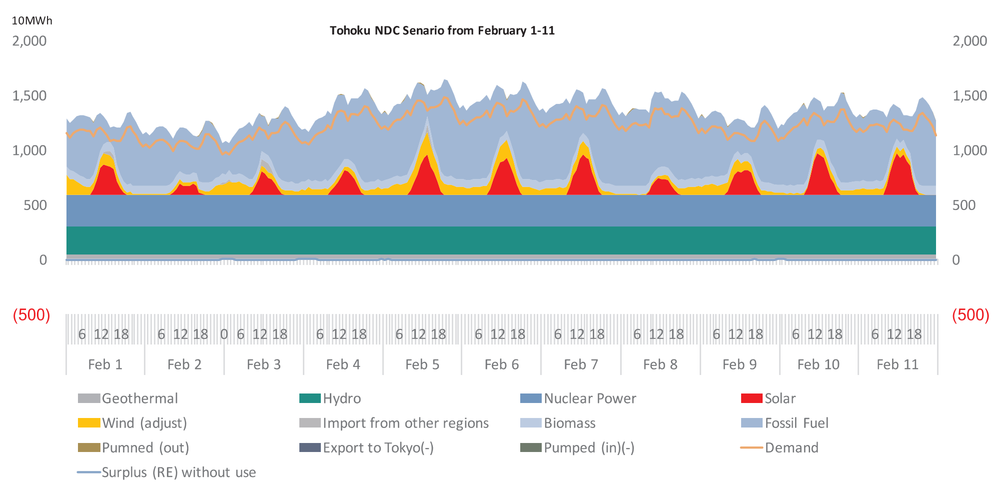



**Fig. 7.** Comparison of simulation results of power generation in 2030 and renewable potentials at the regional level.
Sources: Made from the following sources: Renewable potential (Wakiyama and Kuriyama, 2015) and result of this paper

(8-1)




(8-2)

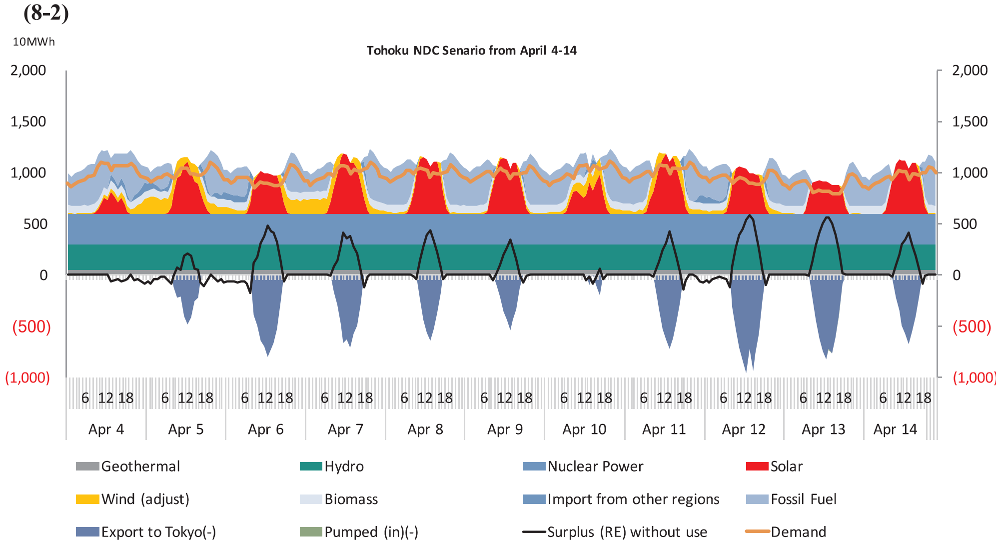



**Fig. 8.** (8-1) Simulation results of demand and supply curve in Tohoku region for February 1–14. (8-2) Simulation results of demand and supply curve in Tohoku region for April 4–14. The figures above illustrate renewable generation potentials on different dates in 2030, when Japan will have achieved the energy mix of the NDC target, which is estimated by applying nationwide aggregated management, flexible priority criteria, and hourly precise control. As an example, in Tohoku, the demand for electricity is relatively high in February due to it being winter, and solar power generation is not large, supply does not exceed the regional demand (left figure). On the other hand, in April, when the electricity demand is not too high due to spring season, and solar power generation is higher, the total electricity supply within the region exceeds the demand, and the renewables generated are transmitted to other regions (right figure).
Source: *Made from the result of this paper* from the result of this paper.

be transferred to other regions. However, even if these renewables are realised, there are issues in transmission to other regions through the interregional grid system, as well as issues with storage within regions, which is needed to control supply (Buckley and Nichola, 2017).

In addition, currently, nuclear power is prioritised as the baseload in the grid over renewables in all regions. This is one of the barriers to accommodating more renewables in the regional supply. Hokkaido, Tohoku, and Kyushu all have certain nuclear potentials, and the renewables must compete against them. For instance, considering Tohoku in February – a time of relatively high electricity demand in the region – nuclear maintains its relatively high ratio in the power supply under the NDC target (Fig. 8–1). Since Tohoku satisfies its electricity demand by supply from within the region, the surplus of renewables could be transmitted to the Tokyo area. However, when we considered a period when electricity demand is low but supply from solar and wind is enough to meet regional demands, such as the generation of up to 11 GWh between 13:00 and 14:00 on 12th April, the surplus is prevented from transmission to the Tokyo area due to the limited cross-regional grid capacity of 7.3 GWh to transmit, as well as the limited maximum grid capacity of 9.8 GWh[40] for the renewable power capacity (Fig. 8–2). The 3 GWh of renewables generated in Tohoku region is, therefore, neither consumed within the region, nor transferable to another region, and is, thus, wasted. Moreover, our analysis reveals that if nuclear is first priority dispatch, even if renewables are second priority over fossil fuels, wind power generation potentially exceeds the electricity supply required to meet the demand within region, and cannot transfer the surplus power generated to other regions due to the limits of the transmission capacity. Surplus wind power generated in Tohoku, Chubu, and Kyushu regions cannot be used, and is wasted. This surplus wind and solar power could be used for compensating deficiency of total national power caused by over estimation of nuclear capacity discussed earlier.

Another finding is an oversupply, not only of renewables and nuclear, but also fossil fuels. This over capacity of power generations comes from mismatches of government plans with established policies, not from the new aggregated criterion. For fossil fuel power generation, current plans for new constructions and replacements total 18 GW of coal-fired power plants, and 29 GW of natural gas-fired power plants,[41] while the total capacities of existing plants are 49 GW, and 73 GW,[42] respectively. Even if we exclude fossil fuel power plants that have exceeded their 40-year lifespan, the capacity is still large compared to the NDC target. Coal, gas, and oil power generation are targeted at 277 TWh, 288 TWh, and 32 TWh in the NDC, respectively. Thus, to meet these targets, the existing plant capacity factors must be approximately 90%, 59% and 50% for coal, gas, and oil, respectively, and if current plans for new constructions and replacements are included, these ratios will be 60%, 42% and 48%, respectively. In the 2DS, if current plans for new construction or replacement are carried out, the capacity factors will need to be reduced by 26%, 35% and 27%, for coal, gas, and oil, respectively. Our analysis shows that in case the priority dispatch order is applied with priority of renewables over fossil fuels, 247 TWh for coal, 299 TWh for gas, and 30 TWh for oil could be dispatched in the NDC scenario, and 103 TWh for coal, 232 TWh for gas, and 15 TWh for oil in case of the 2DS. The capacity factors of these fossil fuels would be further reduced. Although our analysis did not show the significant reduction in coal power generation compared to the NDC target set by the government, it allocates high impact to a coal-fired plant that already has a low capacity factor regarding economic feasibilities to continuously operate the plants.

[40] This paper uses interregional grid connection data from 2016.

[41] Agency for Natural Resources and Energy, "Standards for heat efficiency toward high efficiency thermal power plants" (17 November 2015), in Japanese.

[42] MOE, "Towards a large amount of GHG emission reduction in 2050″ (11 October 2015), Agency for Natural Resources and Energy, "Standards for heat efficiency toward high efficiency thermal power plants" (17 November 2015), in Japanese.

## 5. Discussion

To make economical use of renewables, the analysis results in Section 4 point to a priority dispatch order, and a cross-regional grid connection restructure as the keys to electricity market reform in Japan. The analysis paints a picture of increasing competition between nuclear, renewables, and fossil fuels in the context targets for 2030 and beyond, due to the issues of projected oversupply of power generation and grid connection. Limited capacity of the grid, and the competition are, therefore, of the central issues Japan needs to address; which means that it should clarify its stance on which technology should be prioritised for power generation.

At the same time, the demand-response system could enhance the competition in electricity supply among different electricity sources. The current electricity system reform is considering creating a 'negawatt market', which is aimed at reducing electricity demand. This would increase the competition of electricity supply between nuclear and renewables. The establishment of a baseload electricity generation market based on reform of the current electricity market, which is based on the idea that the current retail market suffers from lack of liquidity due to domination by regional electricity companies chiefly generating power from sources such as hydropower, biomass, nuclear, and geothermal (METI, 2017). Instigating such a market would facilitate access for non-utilities companies to trade in electricity. However, the use of the baseload concept would be obviated in the case where a large renewable capacity was expected, and renewables were to assume a bigger role in the context of a more flexible market (Elliston et al., 2012; Diesendorf, 2007); or if renewables such as wind power were to act as a baseload together with infrastructure for large-scale energy storage (Kempton and Tomić, 2005; Al-musleh et al., 2014). On the contrary, much attention has been globally focused in expanding potentials of renewables by increasing reliability of the electricity grid system that currently prevents a large fraction from renewables, especially solar and wind electricity, through a combination of electricity storage system, and flexible market design, including demand response management (Denholm et al., 2010; Lund et al., 2015; Zhong et al., 2015).

Other issues concerning the planned electricity market reform in Japan is the establishment of a non-fossil fuel power market (electricity generated via non-fossil fuel sources including nuclear, hereinafter referred to as "non-fossil fuel electricity"), which includes nuclear as a non-fossil fuel. This new scheme aims to help reduce the present national burden of the renewable energy surcharge (METI, 2017). Through the non-fossil fuel power market, non-fossil fuel electricity certificates (similar to renewable portfolio standard (RPS) certificates) will be purchased by retail electricity companies willing to increase the ratio of non-fossil fuel electricity in the total electricity supply (METI, 2017). Also aimed at raising use of non-fossil fuel electricity is the Act on Sophisticated Methods of Energy Supply Structures, established in 2011, and revised in 2016.[43] The revision aims to increase the ratio of non-fossil fuel electricity generated by retail electricity power companies, with electricity supplies of over 0.5 TWh to over 44% by 2030 as part of Japan's NDC goal (26% reduction in greenhouse gas emissions between 2013 level by 2030)[44] (Ogasawara, 2016). Furthermore, electrical power companies have set a target emission of 0.37 kgCO2/kWh in their energy mix (JAPC, 2015). However, this raised an issue because non-fossil fuel includes nuclear, and viewed in terms of the baseload market, nuclear will be traded in two different markets. As discussed in Section 4, competition exists between nuclear and renewables under such circumstances, and nuclear has the priority over

[43] METI 2016: http://www.meti.go.jp/committee/sougouenergy/denryoku_gas/kihonseisaku/pdf/004_05_00.pdf.

[44] METI 2015 http://www.meti.go.jp/committee/sougouenergy/denryoku_gas/kihonseisaku/pdf/002_06_00.pdf.

renewables. This paper reveals that if Japan can increase renewables electricity generation reduce the electricity demands more than the government NDC target up to the IEA 2DS level and, Japan could satisfy the electricity demands without nuclear supply. After the Fukushima nuclear accident, it reveals that the external costs of nuclear has been dramatically increased due to the compensation and recovery costs from the disaster as well as the decomposition costs.

## 6. Limitations of this study

The limitations of the method applied in this paper are as follows. First, the model employed applies only to an electricity supply trend for each electricity generation source, i.e., wind and solar power; in actual systems, renewable energy supply would be more complex due to differences in trends and locations. Second (although this issue chiefly affects only Hokkaido and Tohoku), this model does not calculate the level of wind power curtailment needed to satisfy the supply-demand balance. Third, the impact of the diminishing cost of solar PV and wind power generation over time was not accounted for. In fact, solar power technology has developed much more rapidly than predicted in several earlier studies since the current solar capacity of Japan was installed (METI, 2014). Fourth, the model used for analysis of the electricity system needs updating to better reflect the actual situation in which electricity is supplied via several different sources. In addition, increase in costs by introducing renewables, and necessary investment for transmission are not considered. Finally, this study also does not consider one of the government objectives to 'suppress electricity rate'. These will be addressed next.

## 7. Conclusions and policy implications

This study examined the feasible $CO_2$ emission intensity by 2030 under the current electricity system of limited transmission network capacity, and the government plans for electricity market reform towards 2020. It draws inferences to realise more renewable potentials. The findings and suggested policy implementations from this study are described as the followings.

First finding from this study is that, if Japan can generate renewables by maximising the use of regional renewable potentials, they can meet and exceed the carbon intensity reduction target of the electricity sector to 0.29 $kgCO_2$/kWh in the NDC and to 0.17 $kgCO_2$/kWh in the 2DS including nuclear. Regional estimation of electricity generation capacity is key to optimise the use of electricity power generation within a region and across regions. Depending on the region, Japan has the potential to increase renewable energy and improve the carbon intensity reduction target stated in Japan's NDC. Therefore, to achieve the level, as a policy implementation to this issue, strengthening improved grid-interconnectedness and system reform are required, which necessitate the introduction of the priority order system, which ranks available sources of energy in the order of their short-run marginal costs of production, for bringing the sources with the lowest marginal costs online to meet demands before the higher cost sources, and expanding the capacity of the grid system.

Secondly, an issue related to both the current and future markets regarding fossil fuels is that if Japan and the rest of the world aim to achieve the 2DS pledged under the Paris Agreement, supply exceeds the demand due to the increase in renewable energy, and fossil fuels will be in oversupply. Therefore, as a policy implementation of electricity market reform, Japan needs to reconsider building additional fossil fuel plants by strengthening governmental regulations, while considering ways to replace these power plants to renewables by 2030 in a cost-effective way.

Thirdly, this paper finds that while current climate policies intended to achieve the climate target of the NDC, the nuclear potentials towards 2030 are not realistic under current conditions considering their feasibility in terms of the life spans, and the restarting operation of nuclear plants. In addition, the currently discussed electricity market reform, which covers the baseload market and non-fossil fuel power market, is neither an efficient, nor effective mechanism in terms of increasing renewable energy if surplus of electricity generation among nuclear, renewable, and fossil fuels is expected towards 2030 and beyond. Nevertheless, Japan still considers nuclear as cheap baseload electricity and prioritises nuclear power generation. This is one of the main challenges in implementing electricity reform policies to promote renewables. Therefore, as a policy implementation, renewables need political support and systems to operate priority dispatch order over nuclear power generation towards the electricity reform in 2020, and to attract the investment in renewables. Moreover, redirection of governmental budgets from nuclear to renewables is required so that renewables can maximise generation with a combination of technologies and policies by promoting flexible grid operation and strengthening transmission capacity. Local and central governments can also consider maximising renewable potentials by supporting investments in technology for stabilising electricity systems supplied by renewable electricity, such as pumped storage hydropower, storage cells, and demand-response that can store surplus energy until needed.

## Acknowledgements

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## Appendix A. Estimation of electricity supply to the electric grid system

This Appendix provides procedures to estimate electricity supply to an electric grid system in all regions as a whole. As calculation of electricity supply and demand for each hour, an hourly basis electricity supply and demand were calculated by the following equations:

*Demand*

$$d_{2030,i} = D_{2030} * \frac{d_{2014,i}}{\sum_i^n d_{2014,i}} \quad \text{(A7-1)}$$

Where

i: time of electricity demand
n: total number of hours in a year (8760)
$D_{2030,i}$: Electricity demand for each grid for all power plants including distribution losses in 2030 (kWh)
$d_{2030,i}$ : Electricity demand at hour i in 2030 (kW)

$d_{2014,i}$ : Electricity demand at hour i in 2014 (kW)

*Nuclear*

$$e_{n,i} = E_n/8760 \tag{A7-2}$$

Where:

$e_{n,i}$: Electricity supply capacity by nuclear power (kW)
$E_{n,i}$: Potential electricity supply in 2030 by nuclear power (kWh)

*Hydro*

$$e_{h,i} = E_h/8760 \tag{A7-3}$$

Where:

$E_{h,i}$: Potential electricity supply in 2030 by hydropower (kWh)

*Biomass*

$$e_{b,i} = E_b/8760 \tag{A7-4}$$

Where:

$E_{b,i}$: Potential electricity supply in 2030 by biomass power (kWh)

*Geothermal*

$$e_{g,i} = E_g/8760 \tag{A7-5}$$

Where

$E_{g,i}$: E Potential electricity supply in 2030 by geothermal power (kWh)

*Fossil fuels*

$$e_{Tb,i} = E_{Tb}/8760 \tag{A7-6}$$

Where

$E_{Tb,i}$ : Electricity supply in 2030 to be used to adjust supply and demand (kWh)

*Solar power*

$$e_{s,i} = E_{s,i}*\frac{r_i}{\sum_i^n r_i}$$

$$r_i = \frac{\sum_j^m r_{i,j}}{m}$$

Where

i: time of electricity supply
j: monitoring points
n: total number of hours in a year (8760)
m: total number of AMeDAS monitoring points
$E_{s,i}$: Potential electricity supply in 2030 by solar power (kWh)
$r_{i,j}$ : Solar radiation (MJ/m$^2$)

*Wind power*

$$v_{80i,j} = v_{10,i,j}\left(\frac{80}{10}\right)^{\beta_i} \tag{A7-7}$$

$$f_{i,j} = \alpha v_{80i,j}^3 \text{if} v \le 14 f_{i,j} = \alpha(14)_{80i,j}^3 \text{if} 14 < v \le 25 \quad (A7\text{-}8)$$

$$f_{i,j} = 0 \text{if} 25 < v f_i = \frac{\sum_j^m f_{i,j}}{m} \quad (A7\text{-}9)$$

$$e_{wi} = E_s * \frac{f_i}{\sum_i^n f_i} \quad (A7\text{-}10)$$

Where;

i: time of electricity supply
j: monitoring points that located at the place where wind power potential is observed
n: total number of hours in a year (8760)
m: total number of AMeDAS monitoring points
$E_{wi}$ : Potential electricity supply in 2030 by wind power (kWh)
$f_{i,j}$ : Wind force at 80 m height
$v_{10,i,j}$ : Wind speed at 10 m height
$v_{80,i,j}$ : Wind speed at 80 m height
$\alpha$ : Correction factor
: Power exponent for each i, determined in the table below

| **Hour** | **0** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $\beta$ | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.2 | 0.1 | 0.05 |
| **Hour** | **12** | **13** | **14** | **15** | **16** | **17** | **18** | **19** | **20** | **21** | **22** | **23** |
| $\beta$ | 0 | 0 | 0 | 0 | 0 | 0.05 | 0.1 | 0.2 | 0.2 | 0.25 | 0.3 | 0.3 |

Source: DeMarrais (1958); Adachi (1981).

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