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Long-term scenario analysis of nuclear energy and variable renewables in Japan's power generation mix considering flexible power resources

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HIGHLIGHTS

- Authors analyze Japan's long-term scenarios of nuclear and variable renewables.
- The analysis is performed by a dynamic optimal power generation mix model.
- Nuclear phase-out and carbon regulation quadruple power generation cost in 2050.
- Higher PV shares present challenges to make LNGCC a profitable ramp generator.
- Power saving is an economical option to treat an imbalance caused by PV output.

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ABSTRACT

This paper comprehensively analyzes an optimal deployment of variable renewables (VRs) with flexible power resources, such as electricity saving and rechargeable battery, in Japan's long-term power generation mix to 2050 under possible nuclear energy scenarios. The study is performed, employing a dynamic high time-resolution optimal power generation mix model which is formulated as a large-scale linear programming model. Simulation results show that both complete nuclear phase-out and carbon reduction by 80% in 2050 from 2010 encourage VR expansion in the country's power system and cause a quadruple increase of power generation cost at 2050 compared with that under current nuclear capacity and no carbon regulation policy; long-term cost reduction of VR energy system is necessary if VR is positioned as a mainstream for future sustainable power supply. Secondly, higher levels of VR integration decrease the capacity factor of LNG combined cycle (LNGCC), which implies the challenge to assure LNGCC serving as a remunerated ramp generator for VR intermittency. Finally, as an economically optimal solution, electricity saving serves as an important option to integrate massive VR and to treat a seasonal imbalance of its power output in an efficient way.

1. Introduction

After the Fukushima nuclear accident in Japan on March 2011, a lot of attention has been concentrated on renewable energy and energy efficient technology as alternative sources replacing nuclear energy. Recently, the Japanese government has encouraged electric utilities to enhance the proportion of renewable energy in their power grid and to ensure demand flexibility, for minimizing the dependency on nuclear power in the country's energy mix. Particularly after the implementation of feed-in-tariff (FIT) in 2012 by the government, the cumulative installed PV capacity rapidly increased from 7.3 GW in FY 2012 to 14.3 GW in FY 2013 (METI, 2014a). Moreover, PV capacity, which is certified to be built for the future and eligible for FIT, amounts to 65.7 GW as of March 2014 against 231 GW of total utility capacity in Japan (METI, 2014a; IEEJ, 2014). The effects of feed-in tariff (FIT) in Japan for renewable energy have been powerful, because the country's total installed PV capacity, in particular, almost doubled since the start of FIT in July 2012 and Japan has thus experienced a massive PV expansion. In July 2012, Ministry of economy, trade and industry (METI) set the purchase rate in FIT for PV as 42 yen per kW (METI, 2012a). However, since then, METI continuously revised down the rate to reflect lower PV system prices. Currently in FY2014, METI announced that the rate in FIT, for example, for household PV is revised downward to 37 yen per kW (METI, 2014b). By contrast, METI shows preferential renewable energy policies about the set of the rate to offshore wind and other renewables. In FY2014, for

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instance, the rate of offshore wind is newly established, and that of most of other renewables remains unchanged (METI, 2014b). This suggests that the ministry expects the extensive installation of not only PV but also other types of renewable energy. Considering the current trend, PV installation is likely to grow in the power system. Until now, the government sets the target of PV cost reduction and attempts to maximize PV share in the power system from a long-term perspective (NEDO, 2004, 2009).

Solar PV, as well as wind power, is expected to play a critical role for achieving a sustainable energy system. However, the power output of those variable renewables (VRs) is largely constrained by the intermittent availability of climate conditions such as solar insolation and wind speed. If VR penetration becomes predominant in the power grid, a key technical challenge is to maintain the adequate balance of power demand and supply all of the time. Under massive VRs' penetration, power system should effectively control their intermittency, aiming at cost-effectively integrating them with power grid and building an optimal power generation mix. For treating the VR variability, flexible power resources have attracted electricity market, which could facilitate the integration of VR into power system; those could contribute to accommodate higher levels of VR penetration and to guarantee system adequacy through those controllability, such as electricity saving, flexible power generator, tie-line interconnection and electricity storage. For instance, electricity saving, in the form of demand curtailment during periods of high electricity prices, could actively contribute to ensure system flexibility. By implementing those flexible measures, VRs are expected to be actively integrated in power systems. In addition, rechargeable battery is expected to serve as a measure to smooth the volatile output from variable renewable resources which causes voltage and frequency fluctuations in power grid network (Hadjipaschalis et al., 2009; Divya and Østergaard, 2009), besides conventional storage system such as pumped hydro power storage. Recently, for example, NaS (sodium sulfur) and Li-ion batteries have penetrated as commercial energy storage technology finding applications in electric grid support and in wind and PV power integration, bringing favorable benefits to power system control. Furthermore, the introduction of plug-in hybrid vehicle (PHEV) and electric vehicle (EV) has a possibility to serve as distributed storage system (Hu et al., 2014), contributing to manage the output variation of variable renewables.

For planning a sustainable energy system, a high priority should be placed on analyzing the maximization of VR contribution in the nation's power system by taking advantage of those flexible power resources and on discussing the sustainable pathway of future power generation mix. Country such as Japan, where VRs begin to be deployed, should organize better policy to tackle those integration challenges, and this requires the employment of energy system model that can analyze VR installable potential for building a cost-effective and low-carbon power system.

Based on the background, this paper analyzes future possible scenarios of nuclear energy and variable renewables in Japan's power generation mix to 2050, considering flexible power resources, and the authors attempt to identify the challenges associated with integrating large shares of VRs into power systems. The analysis is performed through the development of a dynamic high time-resolution optimal power generation mix model by extending the authors' previous manuscript (Komiyama and Fujii, 2014) which focuses on a single-period analysis (Komiyama et al., 2013a; Komiyama and Fujii, 2013b). The developed model here is a cost minimization model and allows us to assess a long-term optimal deployable pathway of VRs under nuclear energy scenarios in Japan, which can support to make VR investments required to address long-term energy security and climate change imperatives. The highlight of the model is that considered time resolution is 10 min on 365 days of respective forecast horizon to 2050 as well as that flexible power resources are included, that is, quick load-following thermal plants, rechargeable battery and electricity saving. This manuscript comprehensively analyzes the best mix of short-term resources, such as rechargeable battery and electricity saving, and long-term resources, such as nuclear and variable renewables, in a long-term energy system planning, because the deployment of short-term resources influences the load curve profile and has a large impact on the long-term decision-making of the investment for nuclear and variable renewable (IEA, 2014; METI, 2010c). The advantage of a 10-min resolution consists in assessing the impact of short-cycle PV and wind variability on power generation mix in a detailed way. Until now, elaborate analysis on a power generation mix considering VR intermittency has been conducted using a specific energy model (Gallestey et al., 2002; Lund, 2005; Ummels et al., 2007; Xie and Ilic, 2008; Kiviluoma and Meibom, 2010; Troy et. al., 2010a, 2010b; Cheung and Rios-Zalapa, 2011; Denholm and Lund, 2011; Hug-Glanzmann, 2011; Hart and Jacobson, 2011; Keane et al., 2011; NREL, 2012; Schaber et al., 2012; Deanea et al., 2014; Palchak and Denholm, 2014). As far as the authors survey, however, many assessments have not yet been done, comprehensively discussing the positioning of large-scale VR deployment, together with those flexible power resources, in the country's long-term power generation mix with a higher temporal approach such as a 10-min.

This paper is composed of following sections: Section 2 provides the methods including mathematical formulation of a dynamic high time-resolution optimal power generation mix model; Section 3 explains simulation results under respective nuclear and CO_2 regulation scenario, and discusses a positioning of nuclear and VRs in the country's power generation planning; in Section 4, conclusions and political implications are explained and future direction of research is described.

2. Methods

2.1. Dynamic high time-resolution optimal power generation mix model

Expected larger VR penetration raises the significance of energy system model that can analyze the contribution of VR in a long-term energy planning, and positioning of VR should be harmonized with a long-term development of the whole power system. In addition, as VRs considerably penetrates in the system, investments in system flexibility are necessary and the discussion about the optimal timing of those investments become required.

In this paper, the authors discuss long-term scenarios of Japan's power generation mix to 2050 by developing a dynamic high time-resolution optimal power generation mix model in an annual time resolution at a 10-min under various technical constraints. The model is developed, employing a linear programming technique. The minimization of multi-period objective function, which is a summation of discounted annual facility and fuel cost from 2010 to 2050, allows us to identify the best mix strategy of power generation and capacity of power plants in the forecast time period and to estimate the cost-effective planning of power system flexibility to integrate large-scale VRs from a long-term perspective. In order to minimize total system cost under higher VR penetration, strategic energy policy for transforming the power grid is required, and the approach here is suitable to derive power system planning to support such a policy formulation.

In the model, the number of constraints is 18 million, and that of endogenous variables (Table 1) is 7.6 million. An annual calendar year is described by 52,560 time segments (=6 time points per hour × 24 h per day × 365 days per year). Exogenous variables