Energy Policy xx (xxxx) xxxx–xxxx

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

# Assessment of post-Fukushima renewable energy policy in Japan's nation-wide power grid

Ryoichi Komiyama[a,*], Yasumasa Fujii[b]

[a] Resilience Engineering Research Center, The University of Tokyo, Hongo 7-3-1, Bunkyo-ku, Tokyo 113-8656, Japan
[b] Department of Nuclear Engineering and Management, The University of Tokyo, Hongo 7-3-1, Bunkyo-ku, Tokyo 113-8656, Japan

ARTICLE INFO

*Keywords:*
Power grid
Optimization
Renewable energy
Rechargeable battery
Variable renewable
Linear programming

ABSTRACT

This manuscript analyzes an optimal power generation mix in Japan's nation-wide power grid by considering the post-Fukushima energy policy which puts a high priority on expanding renewable energy. The study is performed, employing an optimal power generation mix model which is characterized by detailed geographical resolution derived from 135 nodes and 166 high-voltage power transmission lines with 10-min temporal resolution. Simulated results reveal that renewable energy promotion policy underlies the necessity for capacity expansion of inter- or intra-regional power transmission lines in Japan in order to realize economical power system operation. In addition, the results show that the integration of massive variable renewable (VR) such as PV and wind decreases the capacity factor of power plant including ramp generator and possibly affects that profitability, which implies the challenge to ensure power system adequacy enough to control VR variability.

## 1. Introduction

For Japan which highly relies on the import of energy resource from other countries, the reinforcement of energy security is considered as an important challenge. In global energy market, Japan is one of large energy consumers and importers, becoming fifth in primary energy consumption, third in both petroleum import and consumption, and first in LNG imports. In addition, petroleum holds the largest fraction in the primary energy supply mix (42%), followed by coal (26%) and natural gas (25%), and the fraction of fossil fuels amounts to 93% in 2014 (IEEJ, 2016). The Japanese energy self-sufficiency ratio shows a considerably lower level, only 7% in 2014 (IEEJ, 2016), below that in other developed countries, since the energy supply in Japan depends on imports of almost all fossil fuels. Moreover, Japan is dependent on the Middle East for 83% of its domestic crude oil supply (IEEJ, 2016). Thus, in Japan, nuclear and renewable energy has traditionally played an essential role to ensure domestic energy supply.

However, the impact of Fukushima-Daiichi nuclear accident, caused by Great East Japan Earthquake, is quite influential on the Japanese energy mix and socio-economy, and has caused intensive discussion for rethinking energy policy thereafter which had strongly supported nuclear energy. Obviously, enormous political and technical efforts are required to replace the loss of nuclear power which has been an important base-load technology contributing to energy security and environmental sustainability. After the Fukushima accident, however, alternative energy sources compensating nuclear energy have shown a dramatic increase such as natural gas, coal and solar PV as well as electricity saving. Therefore, the severe nuclear accident is considered to be one of driving force which might lead to the alternative pathway of the country's power grid.

Against that background, this manuscript reviews the Japan's energy transition after the Fukushima and attempts to analyze alternative power supply scenario focusing on renewable energy with an optimal power generation mix model. The model is characterized by considering the power grid topology composed of 135 nodes and 166 high-voltage power transmission lines in Japan with 10-min resolution.

## 2. Methodology

This section firstly reviews energy trend and policy in Japan after the Fukushima nuclear accident for the sake of setting the adequate assumptions for power grid modeling, and secondly explains the structure of an optimal power generation mix model.

### 2.1. Energy trend and policy after Fukushima

#### 2.1.1. Energy trend in Japan

The Fukushima nuclear accident triggered the operation suspension of the country's entire nuclear power plants, which had accounted for around 30% of the country's electricity supply (FEPC, 2016) as shown

* Corresponding author.
*E-mail address:* komiyama@n.t.u-tokyo.ac.jp (R. Komiyama).

http://dx.doi.org/10.1016/j.enpol.2016.11.006
Received 21 May 2016; Received in revised form 2 November 2016; Accepted 3 November 2016
Available online xxxx
0301-4215/ 

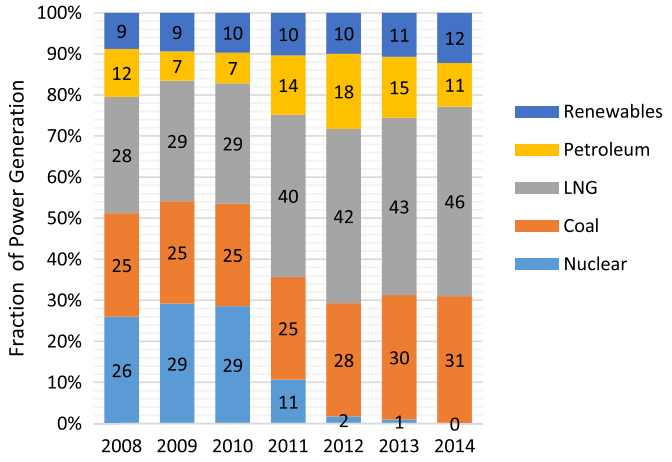


**Fig. 1.** Transition of power generation mix in Japan (FEPC, 2016).

in Fig. 1. After the Fukushima, there has remained strong concerns over the safety of nuclear power plant in the public, and the local government where nuclear power plants are located has not easily provided non-legally bound permission for those restarts. At last, on August 11, 2015, Sendai nuclear power reactor in Kyushu Electric Power Company (Kyuden) restarted its operation, which is the first case of the restart since 2013. Due to the declined utilization of most nuclears since the Fukushima, however, the fraction of thermal power generation over total mix has shown the higher level (94.4% in January 2014) in the last three decades (METI, 2016a).

*2.1.1.1. LNG.* Since the Fukushima, LNG (Liquefied natural gas) has remained a key contributor to power supply in Japan as the world's biggest consumer of the fuel. Substantial increase in LNG after 2011 (Fig. 2) is attributed to power generation to offset the decline in nuclear power. Currently, LNG-fired power generation accounts for almost half of power generation mix in Japan (Fig. 1). As reality, Japan's LNG imports increased from 70.0 million tons (MT) in 2010 to 78.5 MT in 2011, 87.3 MT in 2012, 87.5 MT in 2013, 88.5 MT in 2014 and 85.0 MT in 2015 (MOF, 2016). The increase in LNG consumption has eventually caused the growth of $CO_2$ emissions, and has provided a decline in the country's energy self-sufficiency. In addition, Japan's import payments for LNG in 2014 were a record high at 7.9 trillion yen, more than doubling from 3.5 trillion yen in 2010, although the payment is decreasing to 5.5 trillion yen in 2015 (MOF, 2016) due to the recent collapse of crude oil price since the end of 2014.

*2.1.1.2. Coal.* Together with LNG, coal consumption has increased in power sector. As one of key resources, Japan is conventionally

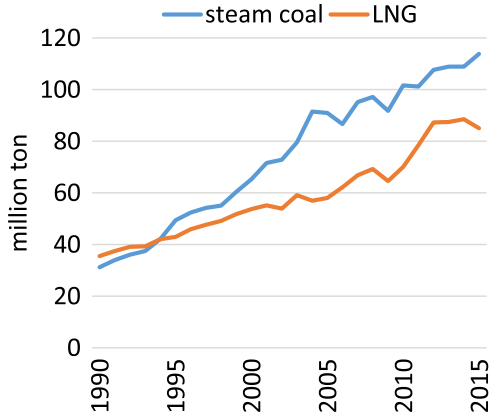


**Fig. 2.** Imports of LNG and steam coal in Japan (MOF, 2016).

prominent at its coal promotion in power sector among developed economies. And in terms of energy security, coal is regarded as an important energy resource for purchasing other fuel at competitive price through the employment of coal as a bargaining power in trade negotiation. In general, coal holds an important advantage of its economical competitiveness, although it has an environmental disadvantage of its higher carbon intensity. As most nuclear power plants in Japan remain shut down since the Fukushima, Japanese utility companies have been eager for the increased use of coal and actually began planning new operation of coal-fired power plants in order to enhance the capability of economical power supply, mainly because coal is less expensive than natural gas. Like other resources, coal price has collapsed, almost halving over the past several years and increasing its economical attractiveness to power companies. Actually, record imports of 114 million tons of steam coal was observed in 2015, doubling the amount reached at 1998 (Fig. 2).

If nuclear restart does not proceed as expected by the government, the power companies might depend further on coal as the preferred economical power source. In addition, deregulation of small-scale retail electricity market that began in April 2016 will intensify price competition between existing utilities and new entrants (Asano and Goto, 2013), and it further causes electricity industry dashed more toward coal. As shown in Table 1 compiled from (OCCTO, 2015; MOE, 2015a, 2015b), major power companies have a bunch of plans to newly construct or expand the capacity of coal-fired power plant, and total 12 gigawatts (GW) of additional coal-fired capacities are under consideration. Besides those plans, an increasing number of small-scale coal-fired plants are planned to be installed with total capacity of 1420 MW (MW) by 14 corporations (MOE, 2015b), which does not require the official environmental assessment for its construction. In total, there are currently plans to build or expand 31 coal-fired power plants across Japan, with total 14 GW of additional coal-fired capacity.

*2.1.1.3. Renewable.* As explained so far, fossil fuel serves as main alternative source substituting nuclear power after the Fukushima. However, more expectation has been concentrated on renewable energy as socially preferable option, since those are domestic and

**Table 1**
Current plans of coal fired power plants in Japan.

| Power Company | Power Station | Capacity [MW] | Start of Building | Start of Operation |
|---|---|---|---|---|
| New Construction | | | | |
| Kyushu | Matsuura No.2 | 1000 | 2001 | 2020 |
| JPOWER | Takehara No.1 | 600 | 2015 | 2020 |
| Tohoku | Noshiro No.3 | 600 | 2016 | 2020 |
| Tokyo | Nakoso | 500 | 2016 | 2020 |
| Tokyo | Hirono | 500 | 2016 | 2020 |
| Kashima Power | Kashima No.2 | 650 | 2016 | 2020 |
| Yamaguchi-Ube Power | Nishiokinoyama | 1200 | 2017 | 2023–2025 |
| Chubu | Taketoyo No.5 | 1070 | 2018 | 2022 |
| Chugoku | Misumi No.2 | 1000 | 2018 | 2022 |
| Kobe Steel | Kobe Steel | 1300 | 2018 | 2021–2022 |
| Hitachinaka Gen. | Hitachinaka No.1 | 650 | 2019 | 2021 |
| Shikoku | Saijou No.1 | 500 | 2019 | 2022 |
| Expansion | | | | |
| JPOWER | Matsuura No.2 | +575 | 2015 | 2015 |
| JPOWER | Isogo No.2 | +38 | 2017 | 2017 |
| JPOWER | Takasago No.1 and 2 | +700 | 2018 | 2021–2027 |
| Fuel Switching (from petroleum to coal) | | | | |
| Kansai | Akou No.1 | 600 | – | 2020 |
| Kansai | Akou No.2 | 600 | – | 2020 |