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100% renewable energy system in Japan: Smoothening and ancillary services

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HIGHLIGHTS

- Hourly simulation using real atmospheric data.
- Reliability assessment of 100% renewable energy grid.
- Feasibility of the system is assured provided large-scale implementation of batteries.

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ABSTRACT

In the aftermath of the Paris Agreements, many countries around the globe have pledged to reduce the amount of greenhouse gas emissions being released into the atmosphere. To do so, it is important that the amount of renewable energy in the electricity grid increases. However, there are worries of the capacity of the grid to cope with intermittent energy sources. To assess the feasibility of a 100% renewable energy system in Japan, the authors conducted an hourly simulation of future electricity production based on wind, solar and tidal data. The system was shown to be stable, and the authors calculated the required capacity of electrical batteries that would be necessary to balance such a system.

1. Introduction

One of the most important events of recent times in Japan took place on the 11th of March 2011, when a large earthquake offshore of its northeast region created a tsunami that went on to devastate large parts of the country's coastline. The tsunami overtopped coastal defences and brought down the cooling systems at the Fukushima Dai-ichi nuclear power plan, ultimately resulting in the release of large amounts of radioactive material into the environment. As a result of this accident and other earthquake related damage, and also due to large public opposition to this source of energy [1], all nuclear reactors were shut down. The newly created Nuclear Regulation Authority (*Genshiryoku Kisei Iinkai*, NRA) began carrying out safety inspections and stress test assessments in 25 of Japan's existing nuclear power reactors, though it is unclear how many will eventually be brought back online. Public opinion, supported by district court injunctions and prohibitive retrofitting costs, are some of the major obstacles to the restart of the idle nuclear fleet.

To compensate for the offline nuclear reactors a significant amount of fossil fuel power was brought online, which resulted in increases in

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the imports of natural gas and heavy fuel oil (up by 36% and 121%, respectively) [2]. This has had a significant economic and environmental impact [3], given the rise in fossil fuel imports and the increase in greenhouse gas (GHG) emissions. Responding to these new circumstances, the Agency for Natural Resources and Energy released an Energy White Paper detailing the country's long-term energy supply and demand plan [4]. This strategy reflects the need to guarantee a secure, economically effective and environmentally friendly energy supply, and reinforces the need to restart the country's idle nuclear fleet. Thus, there are proposals for the nuclear share in the power generation portfolio to be 20–22% by 2030, which is equivalent to an installed capacity of the 30–35 GW [5]. However, by 2030 only 20GW of installed capacity will be operable (considering a plant life time of 40 years) and, as earlier stated, the construction of new nuclear power plants is highly unlikely under the present conjecture of nuclear safety concerns in the country (although completion of plants currently under construction is probable). If Japan is seriously committed to achieving the Nationally Determined Contribution (NDC), ratified under the Paris Agreement, which pledges a GHG emission reduction target of 26% below 2013 emission levels by 2030 [6,7], an aggressive deployment of renewable energy will be required.

A number of studies in the past [3,8–12] have examined future possible energy generation mixes in Japan, though these typically do not evaluate the reliability and actual feasibility of the proposed energy scenarios. Essentially, most authors simplify the analysis to yearly or monthly averages, ignoring daily and hourly supply/demand fluctuations [13,14]. However, taking into account such fluctuations is crucial when dealing with high penetration rates of intermittent renewable energy [15], as wind strength and solar radiation patterns vary according to time, making the balancing of variable demand and supply challenging. Statistical studies that do not take into account these geographical and periodical variations, and instead rely on country-level data, are potentially flawed. Despite this obvious flaw, to the authors' knowledge little research has incorporated such variables into the analysis of future scenarios for the case of Japan [15–18], and Heard et al. [19] found only 24 studies that have modelled 100% renewable systems in other countries (for example that in Lund et al. [20]).

Some authors believe that a high penetration of intermittent renewable power sources poses a problem to traditional grid systems [21]. These grids were not originally designed to deal with sudden peaks and falls in the electricity fed into them [22], though for large grids this can be attenuated due to smoothening, as unfavourable weather conditions in one part of a country will often be compensated by better conditions elsewhere [15], and the use of storage (batteries, pumped hydro systems or hydrogen storage) and integrated transmission lines. To take advantage of the smoothening effect it is essential to have an efficient long-distance transmission grid and to employ smart-grid technologies with controllable demand and supply. More accurate models should include the analysis and study of geo-physical variables on an hourly basis (or ideally a minute-by-minute basis, if data and computing power are available). Examples of long-distance transmission can already be found elsewhere, for instance, the Netherlands transmits its surplus electricity to Norway, where it is used to power hydro pumped storage systems [23] or in Brazil, with the world's longest transmission link (2400 km), which connects the Northeast hydropower plants with the large power demand in the South-Central region.

The creation of a low impact energy sector in Japan will probably require the use of electric storage and smart-control technologies [24–27]. A number of different possible systems have been envisaged, such as the use of PV generation with various types of batteries, or wind power and hydrogen [28–32]. For the case of Japan, it has been estimated that around 40 TWh of storage would be needed to compensate for the extra energy that was required to power air conditioning units in the summer, though a system that uses only solar, wind, hydroelectricity and biomass is likely to have trouble meeting demand [33]. However, it is worth noting that after 2011 a number of power saving strategies have been implemented in Japan during the summer months [34], resulting in about 15–20% decrease in the electricity demand during this period.

Heard et al. [19] pointed out that in order to be feasible, a 100% renewable energy system must meet four different criteria:

1. Criterion 1: The electricity demand to which supply will be matched must be projected realistically over the future time interval of interest.
2. Criterion 2: The proposed supply of electricity must be simulated/calculated to be capable of meeting the real time demand for electricity for any given year, together with an additional back-up margin, to within regulated reliability limits, in all plausible climatic conditions.
3. Criterion 3: Any transmission requirements for newly installed capacity and/or growth in supply must be described and mapped to demonstrate delivery of generated electricity to the user network such that supply meets both projected demand and reliability standards.
4. Criterion 4: The proposed system must show how critical ancillary services will be provided to ensure power quality and the reliable operation of the network, including distribution requirements.

These authors note how to date no literature on the subject has completely addressed such criteria, noting how the only study in Japan on their list (that of Esteban et al. [35]) fails to discuss Criterions 3 and 4 altogether, and even the best ranking studies in their list (by the Australian Energy Market Operator [36]) also fail to significantly address it. Thus, in the present work the authors set out to ascertain whether a 100% renewable energy system in Japan could be feasible from the point of view of transmission and the provision of ancillary services. Given that Heard et al. [19] claim that no study satisfied their four criteria, the originality of the present work lies precisely in showing that it is possible for a scientific study to satisfy all of their criteria, and prove that a 100% renewable energy system can work.

To do so, the study modifies and updates the methodology of Esteban et al. [35], (which considers only solar and wind power) to encompass other types of intermittent energy, in this case ocean energy technologies. The model simulates future electricity production based on the actual historical hourly wind, solar and tidal data (for a sample historical year in the past), and attempts to ensure that electricity demand in the year 2030 can be met. Other non-intermittent technologies, such as hydropower, biomass and geothermal are also included in the simulation. The model will then be used to calculate how the provision of ancillary services could work for the systems proposed.

2. Criterion 1: projection of future electricity demand

Heard et al. [19] are satisfied that the system described by Esteban et al. [35] adequately meets their minimum requirements for this criterion. This section summarises the projections for future electricity for the present model, and the assumptions on which they are based, following Esteban et al. [35].

2.1. Current Japanese electricity mix and future demand

The country currently consumes around 990 TWh of electricity per year, though this is likely to be significantly influenced by future socio-economic and demographic changes, as well as changes in technology uses and efficiency. Even before the 2011 earthquake the power generation matrix in Japan was heavily dependent on fossil fuel technologies, which produced 64% of the electricity used in the country [37], with renewable sources (mostly in the form of hydropower) representing only around 10% of the mix [37]. After the events of 2011