

100% renewable energy system in Japan: Smoothing 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 plant, 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 smoothing, 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 smoothing 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 Criteria 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

the Japanese government initiated a series of policies aimed at reforming the electricity sector, diversifying the electricity mix and encouraging independent producers. One of these is the establishment of a Feed-In Tariff (FIT) system for renewable electricity suppliers [17,38,39], with initially high tariffs which have slowly been falling [40]. As a result, domestic shipments of solar modules increased by 171% between 2011 and 2012, and in 2016 there was 42.8GW of solar power installed in Japan, with a significant amount more in the pipeline [41].

2.2. Population decline

To estimate future levels of electricity demand it is necessary to take into account population change. The fertility rate in Japan has fallen below the level necessary to maintain a stable population, and the overall population of the country has already started to decline. The Japanese National Institute of Population and Social Security Research [42] has forecast that by 2030 the population will have decreased to around 117 million (from the present 127 million). Although there are likely to be many regional variations (given that rural areas are experiencing more pronounced declines than major cities [43], where the population remains stable), the present work will assume the rate of depopulation to be identical among regions [44].

2.3. Estimation of Japanese GDP and electricity consumption scenarios by 2030

For the last two decades Japanese GDP growth has been mostly flat (possibly as a consequence of the stagnating/decreasing population), and according to the Japan Centre for Economic Research GDP annual growth rate per capita is forecast as 0.2% between 2016 and 2025 [45]. Future electricity demand is thus likely to be mostly affected by the demographics of the country and the possibility of a large scale uptake in the use of electricity vehicles or other technologies.

As such, for the simulations in this study, the authors used four different demand scenarios (summarised in Table 1):

- **Scenario A.** Reduction in demand to 60% of its current level, following Tsuchiya [18], meaning a total production of 594TWh per year. The rationale for this would derive from incremental future increases in energy efficiency, a decrease in the population, and an almost negligible use of electric vehicles by 2030.
- **Scenario B.** 33% decrease in current electricity demand by 2030, due to the extensive use of electric vehicles. This follows the work outlined in [3], in which the authors forecast the overall aggregated electricity demand in 2030 as a product of the estimated electricity demand per capita and the predicted population around this time. Essentially, per capita electricity demand was estimated by fitting a multiple regression on historical data from 1980 to 2010, using GDP per capita, and industrial and residential price of electricity as predictors of per capita demand. Thus, by the year 2030 the total yearly electricity demand is forecast to be 823 TWh, in line with [3].
- **Scenario C.** This is a scenario that assumes that the electricity demand in Japan would stay the same as that at present (i.e. 990 TWh).
- **Scenario D.** This is similar to the energy scenario used by Esteban

et al. [35], estimating that energy demand will stay the same, but that electrification ratios will greatly increase [45]. Essentially, this would mean that total demand would be 1.5 times higher than that in 2005, and would rise from 990 TWh in 2005 to 1400 TWh in 2030. This scenario would appear extreme, given the demographic scenarios presented earlier [43], though there is always the (remote) possibility that the government will change its long term stance on migration and allow a greater influx of immigrants into the country.

2.4. Fluctuations in energy consumption

Japan has three climate zones, though much of it is classified as “humid subtropical” with four distinct seasons, and there is a substantial fluctuation in the patterns of electricity consumption between them, as shown in Fig. 1. Electricity consumption peaks in winter (due to heating requirements) and in summer (due to the high usage of air-conditioning units), and the annual load factor is currently approximately 60% on average, (rather low compared with 70% to 80% in Europe [46]). On top of these long-term seasonal variations, there are also short-term fluctuations between daytime and night time [15].

The required electrical load for each hour of the day in the year 2030 was derived by using historical demand for the year 2015 (see Fig. 1), and scaled to the year 2030 (see [33]), using data obtained from the Federation of Electric Power Companies of Japan [47]. This scaling up (or down) of the electricity demand was conducted linearly. In other words, it was assumed that the overall pattern of the electricity demand throughout the day will stay constant.

3. Criterion 2: methodology used must ensure real-time demand can be met, by using plausible real-time data on weather and ocean conditions

Heard et al. [19] emphasise how a future 100% renewable electricity system must have high reliability (> 99.9%), meaning that it must ensure a constant (i.e. available at all times and/or fully dispatchable (able to be called-up or withdrawn at any time in response to demand changes)) supply of electricity.

3.1. Methodology outline, and reliability of the overall system

To ensure that such a system could be realized, the authors improved on the methodology of Esteban et al. [35] by expanding the types of energy sources considered (most notably through the inclusion of ocean energy technologies). Essentially, this method uses historical meteorological and ocean data to estimate the amount of energy that can be produced by a variety of energy devices, be it solar panels or wind or tidal turbines (see Tables 2 and 3).

It was assumed that solar panels would be mostly installed in cities and their vicinity, and the 15 biggest cities in Japan were considered. Wind power was assumed to follow current patterns of distribution, clustered around 24 existing wind farms. The eight straightings with best tidal resources were considered for tidal energy.

The energy produced by intermittent sources using the real meteorological data during each hour of each day was then checked against total demand, as shown in Table 2. If solar, wind and ocean power were unable to provide for the electricity demand, the simulation then started to access other types of energy sources to balance demand. In the first instance it will resort to geothermal, then hydropower, then biomass, and finally to hydro pumped-storage. Finally, the energy stored in batteries will be used, if the system cannot produce enough electricity.

The electricity produced by solar panels in a given hour is given by the equation:

$$P_S = I \times \eta \times F_{temp} \times F_{inv} \times F_{other} \quad (1)$$

where I is the irradiance (kW/m^2), η is the conversion efficiency of the

Table 1
Summary of demand scenarios.

Scenario	Change in electricity demand	Total electricity demand (TWh/year)	Reference
A	–60%	594	[18]
B	–33%	823	[3]
C	No Change	990	–
D	+150%	1440	[35,45]

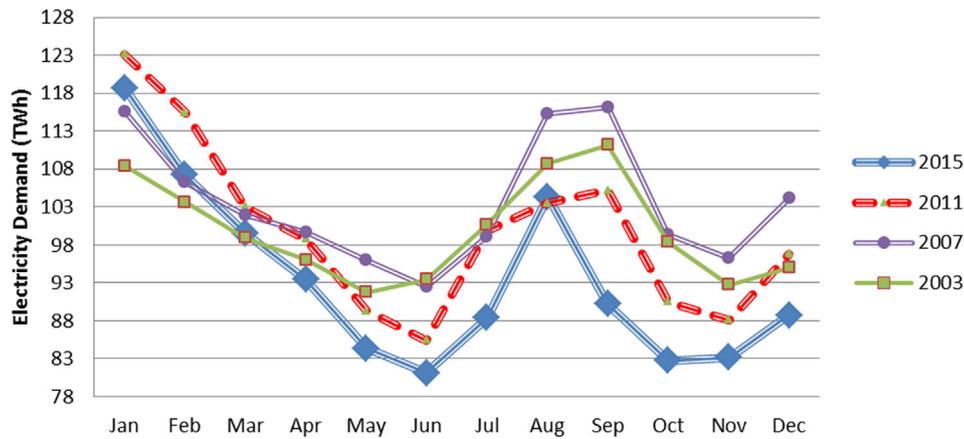


Fig. 1. Trends in electricity demand in Japan between 2003 and 2015.

Table 2
Assumed characteristics of solar cells in the year 2030 [48].

Parameter	Symbol	Value	Unit/notes
Peak power of solar cells	R_{CW}	0.5	kW/m ²
Conversion efficiency	H	20%	
Efficiency of inverter	F_{inv}	95%	
Efficiency for other factors	F_{other}	95%	
Efficiency at low Temperature	F_{temp}	90%	Dec-Feb
Efficiency at moderate Temperature	F_{temp}	85%	Mar-May & Sep-Nov
Efficiency at high Temperature	F_{temp}	80%	Jun-Aug
Azimuth angle		0	Degrees
Inclination to horizontal of solar panel		30	Degrees

Table 3
Characteristics of wind turbine units in 2030 [49].

Parameter	Symbol	Value	Unit
Rotor Diameter	d_r	120–150	M
Cut-in Speed	V_C	3	m/s
Rated Speed	V_R	10	m/s
Cut-out Speed	V_F	30	m/s
Air Density	ρ_a	1.205	kg/m ³
Rated capacity	R_{CW}	10	MW

solar panels, and F_{temp} , F_{in} , F_{other} are the efficiencies of the temperature, inverter and other factors, respectively. The values of these parameters are summarized in Table 2.

The electric power delivered at any one given hour, P_W , by a wind turbine is considered to depend on wind speed, and can be expressed by the following set of equations:

$$\begin{aligned}
 P_W &= R_{CW} \frac{V^k - V_C^k}{V_R^k - V_C^k} \text{ for } V_C \leq V \leq V_R \\
 P_W &= R_{CW} \text{ for } V_R \leq V \leq V_F \\
 P_W &= 0 \text{ Otherwise}
 \end{aligned}
 \tag{2}$$

where V is the actual wind speed at the turbine, k a factor depending on the turbine characteristics, R_{CW} is the rated output power, V_C , V_R and V_F are speeds for cut-in, rated and cut-off. A summary of the parameters used is given in Table 3.

The time averaged power density P [W/m²] available in a tidal regime can be approximated by

$$P = \frac{1}{2} \rho K_s K_n U^3
 \tag{3}$$

where ρ is water density (1020 kg/m³), U is maximum flow speed, $K_s = 0.424$ is a velocity shape factor for sinusoidal flow, and $K_n = 0.57$ is a spring-neap factor (which assumes that maximum neap current speed is 60% of maximum spring current).

For solar and wind, the data from AMEDAS (Automated Meteorological Data Acquisition System of the Japan Meteorological Agency) [47] for the year 2001 was used. Data for the strength of the tidal flows was obtained from NOWPHAS for the year 2001. Throughout all the simulations carried the authors calculated the reliability of the system, in terms of it being able to service the demand, to ensure that a reliability > 99.9% could be achieved (as per the criteria set-out by Heard et al. [19]).

It is important to note that the current system uses hourly weather data, and the authors contend that this is appropriate to study a given area. While Heard et al. [19] emphasise that one-hour timescales will not account for rapid fluctuations in solar photovoltaic output, the authors would like to emphasise that any quick variations induced by the passage of clouds would be smoothed out over a city and regional scale. Moreover, once grid parity is achieved by solar PV, it is likely that FiTs will disappear, and thus the electricity produced will be used directly by households, commerce and industries, and only surplus electricity will be sold to the grid. Hence, small timescale fluctuations will be dealt with by battery systems installed close to the PV units, and thus taking into account such small timescale variations is unnecessary.

3.2. Solar and wind composition scenarios

A number of different mixes of solar to wind scenarios were run. Esteban et al. [15] calculated that the optimum solar to wind installed capacity for a system that had the maximum load during summer months had a mix Ψ of 31%:

$$\psi = \frac{R_{CS}}{R_{CW} + R_{CS}}
 \tag{4}$$

where R_{CS} is the total installed rated capacity of all solar panels and R_{CW} the installed rated capacity of all wind turbines.

However, given recent gains in efficiency and energy saving, electricity usage now peaks during winter months, making such a system less advantageous. Thus, a system with an equal nominal wind and solar installed capacity, and one with high penetration of wind power, were also analysed. These scenarios will be referred to as the high wind ($\Psi = 31\%$), balanced ($\Psi = 50\%$), and high solar ($\Psi = 69\%$) scenarios.

3.3. Location of solar, wind and ocean energy devices

The method simulates the production of energy at a variety of points (“farms”) in Japan, taking into account the climatic/tidal conditions at each point (see Esteban et al. [15] for more details). “Solar farms” were considered to be installed on the rooftops of major population centres, and the weather conditions of 15 of the 47 prefectural capitals in Japan were used to simulate generation. The conversion efficiency was assumed to be 20%, as outlined in Table 2 [15]. “Wind farms” were

Table 4
Capacity factor complementary types of energy sources [50].

Energy type	Capacity factor (%)	Installed capacity (GW)
Hydropower	45%	27.6
Tidal Power	Depends on farm	0.67
Biomass	80%	15.9
Geothermal Power	80%	11.8
Pumped Storage	48% ^a	19.8

^a Note: This value is the efficiency of an unmodified Pump-as-Turbine (PAT). The roundtrip efficiency of pumped storage is typically ~75% for a reversible pump/turbine, and > 80% for separate, dedicated pump and turbine.

considered to be located in the areas where they are currently located, and thus future scenarios represent a “scaling-up” of these farms. However, an allowance is also made for other wind farms to be located close to regional capitals and “solar farms”, so these areas also form part of the potential future wind farms, with a total of 24 wind farms being considered. The maximum rated capacity of wind turbines was set at 10 MW, see [15]), as shown in Table 3. For the case of “tidal farms”, the methodology outlined in Bricker et al. [48] was used, which can estimate the amount of electricity that could be produced at the most promising tidal straits in Japan. However, at present it appears that this resource is rather limited, and as such only the most promising sites identified in Bricker et al. [48] are used (see Table 4). The capacity factor and installed capacity of other types of energy used are also given in Table 4.

3.4. Non-intermittent renewable energy resources

If intermittent sources cannot cover electricity demand, the simulation will then start to access other types of energy sources. For the case of pump-storage the installed capacity was set as 19.4 GW and the maximum storage capacity would be 1.2 PJ [20]. This is basically the same as current capacity, so the assumption is that no new pumped-storage will be built. Conventional hydropower would stay constant, with no new dams built. The capacity factors and installed capacity of each of these types of units is outlined in Table 4.

3.5. Balancing the system through electricity storage (batteries)

If after using all these sources the system still cannot meet demand, then the electricity from the batteries of electric cars is accessed. Different scenarios regarding the total size of the battery pool were calculated, and for reference it is useful to consider that a Tesla S76 model has a battery of 67 kWh, meaning that 22.68 million of these cars would have a storage capacity of 1520 GWh.

The transmission capacity from batteries to grid and vice versa was assumed to be high, at around 120 GW, as in many cases the batteries would only be used to directly power appliances within a house. The conversion (round-trip) efficiency of batteries was assumed to be 90% [18], with Fig. 2 showing an example of the simulation providing for demand for one sample day.

3.6. The impact of extreme climate events

Heart et al. [19] mention that it is necessary for a 100% renewable energy system to address the impact of extreme climate events. For the case of the Japanese electricity grid, it is clear that there are considerable risks facing any energy system [17], given the large potential for natural disasters in the country (be they earthquakes, tsunamis, typhoons or volcanic eruptions). Given such constraints, which are peculiar to the case of Japan, and the experience of the 2011 event, it is likely that a 100% renewable dispersed system would be more reliable than a centralised system that could be more easily disrupted by impacts to several power plants [11]. Given such issues and the need for

redundant capacity to cope with disasters, it is unlikely that any transitory weather anomaly would be likely to disrupt the system more than when all of the 54 nuclear reactors in the country were brought offline as a consequence of the 2011 Tohoku Earthquake and Tsunami.

4. Criterion 3: transmission for newly installed capacity

As outlined earlier, the present simulation assumes that the electricity produced by PV will be consumed (to a large extent) by those who are producing it, as it would be installed mostly in the rooftops of houses or businesses. Excess production would be stored in batteries in the vicinity, making use of the distribution network. Eventually, any excess capacity would be distributed to other cities, using the transmission grid. However, given that most electricity would be consumed close to the point of production, it is expected that the requirements placed on the grid would be modest. The challenge comes from the integration of large amounts of wind power into the system, which would mostly be centred around the northern parts of the country. This is likely to require the upgrading of some parts of the transmission grid, and it might be necessary to create a low-loss transmission line that connects Aomori and Hokkaido to the highly densely populated areas around Greater Tokyo (with a population of around 36 million, it is expected that much of the battery storage capacity would be concentrated in this area). The overall distance of such a line would be in the range of 700–1000 km, and well within the limits of what the Japanese government could afford.

5. Criterion 4: provision of ancillary services

Japan has two different grid systems, which generate electricity at either 50 or 60 Hz, with a minimal degree of connection between them. The frequency of both systems would have to be maintained close to the prescribed standards in any future grid, a job that currently is provided by the inertia of “synchronous” generators, where electricity is generated through turbines spinning in unison at close to the regulated standard (Heart et al. [19]). Wind and solar PV do not currently provide such frequency-control ancillary services [36], and the increase in intermittent renewable generation is already leading to a scarcity of support services, increasing the risk of breaching reliability standards [19].

In this section the authors will explore the average and minimum synchronous capacity of each of the demand and energy mix scenarios. To do so, the authors have considered that hydropower, biomass, geothermal and pumped storage are the only types of energy that can provide these ancillary services.

5.1. Scenarios A and B: reduction in future electricity demand

The amount of required solar and wind capacity in the system (assuming that all other types of energy plants remain constant, see Table 4) is influenced by the amount of electric battery storage, as shown in Fig. 2 (for scenario A, representing a decrease in electricity use and no electric vehicles, all the batteries would essentially be installations dedicated exclusively to balancing the power system). Essentially, the higher the total storage capacity of batteries, the lower the overall required installed capacity of solar or wind, as more electricity during periods of good atmospheric conditions can be stored and used later on (see Figs. 3 and 5). Any electricity that cannot be stored is essentially dumped, which will be represented in later figures as “wastage”. Note that the system transfers unused electricity into the batteries during times of high production of electricity from intermittent sources, which can then be returned to the grid when conditions are not as conducive to the production of electricity (with Fig. 2 showing one such period). Overall, given that the peak in electricity use is during winter, high wind scenarios appear more interesting than high solar scenarios, as during winter solar radiation is weaker (Figs. 3 and 5).

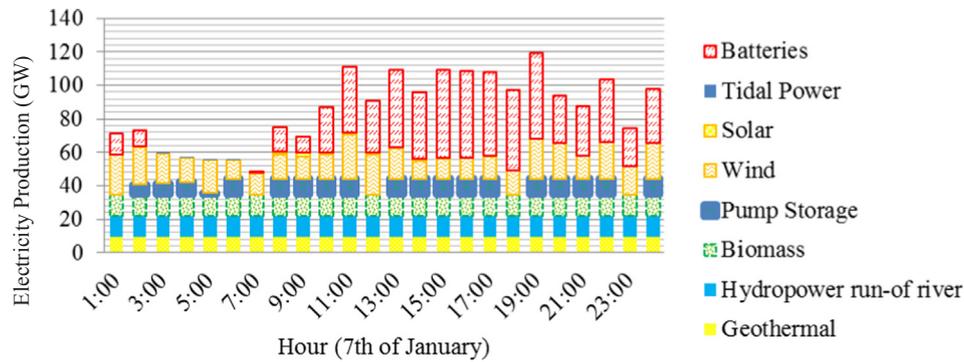


Fig. 2. Sample of one generation day (Energy Scenario A, for a $\Psi = 31\%$, 68 GW solar and 154 GW wind). Batteries are charged during periods when the demand for electricity is lower than the supply (typically at night, or on days when production is high. This figure represents a day in which power from wind and solar is limited, meaning that much of the load comes from pumped storage and batteries).

It is interesting to note that the installed capacities shown in Scenario A are not significantly different to what has already been planned in Japan for the case of solar (Fig. 3), though they would require a significant increase in wind penetration. However, the picture is very different for the case of Scenario B, with the required capacities significantly larger than what is currently planned (Fig. 5). Also, for this case a significant amount of electricity production is wasted, which could be almost up to 30% of production for the lower battery scenarios (Fig. 6). Essentially, once the batteries are fully charged, any additional production from intermittent sources would be wasted, which would clearly have an effect on the overall profitability of such as system. Further increases in battery storage only seem to slowly reduce this problem, and it would probably be advantageous to use a different long-term storage mechanism, such as hydrogen, to overcome this problem.

In terms of the synchronous capacity in the system, scenario A scores quite well, with average values of around 50% or higher. The minimum amount of electricity produced from synchronous sources at any one point in the year is approximately one third of all electricity produced. This drops noticeably for the case of scenario B, with a minimum generation of power from synchronous sources of around 25% (see Fig. 4).

5.2. Scenarios C and D: no change or increase in future electricity demand

Scenario C represents an artificial scenario that would assume everything stays the same as present conditions, and that overall energy consumption throughout the year remains at 990 TWh. This would require the installation of far more solar power than is currently planned.

For the high solar scenarios Fig. 7 shows how this could be between 411 GW –for a higher range of installation of battery storage of 13,780 GWh- to 659 GW – for a lower range of batteries of 1520 GWh-, which would be 4 to 6 times what is currently installed or approved in Japan. This does not seem entirely unrealistic, though the expansion on wind power required would be significant, at between 187 GW to 300 GW. This is plausible, as several countries around the world (China, USA or Germany) have installed total capacities that are in those orders of magnitude (Germany has in excess of 50 GW, the USA has over 80 GW and China over 168 GW). Nevertheless, the challenge would be significant, given Japan’s comparatively inferior wind resources, and could require the use of significant amounts of wind turbines around the northern parts of the country. More serious would be the drop in synchronous power generation, which would reach yearly minimums of just over 20%, as shown in Fig. 8. Energy wastage would be significant for the low battery storage scenarios (42% for an installed battery storage of 1520 GWh, as shown in Fig. 8), and to be financially viable would inevitably required large amounts of batteries to be installed. Wastage can be reduced to under 10% for the higher battery storage scenarios shown in Fig. 8, but the reduction in wastage gradually flattens, indicating how introducing extra batteries gradually has less influence on the reduction of wastage. The calculation of the cost optimisation of the system is outside of the scope of this paper, but it is clear that there would be a point where the reduction of electricity waste would no longer be justified by connecting more batteries into the system, and that this issue needs to be carefully analysed in the future.

Scenario D estimates that electrification ratios will greatly increase, and that total demand would be 1.5 times higher than that in 2005, and

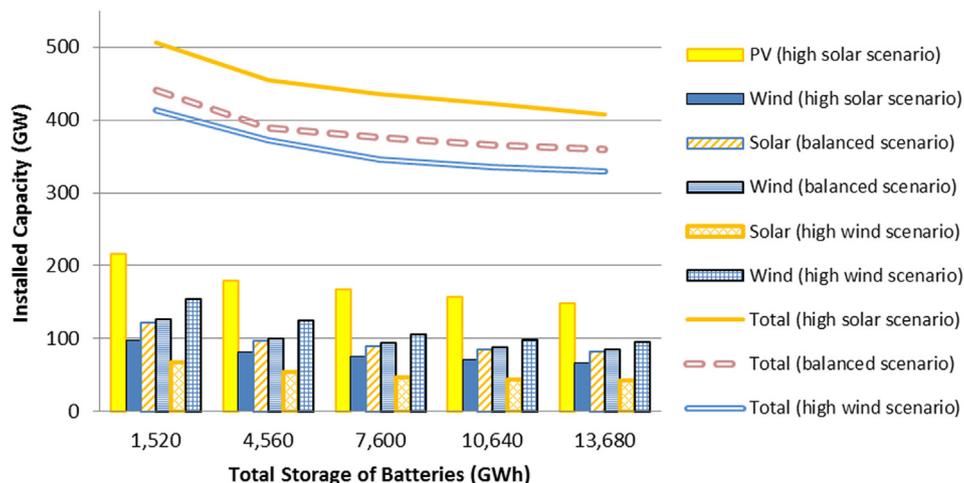


Fig. 3. Required solar and wind installed capacity for energy demand scenario A (60% reduction in overall electricity use), for different storage capacities.

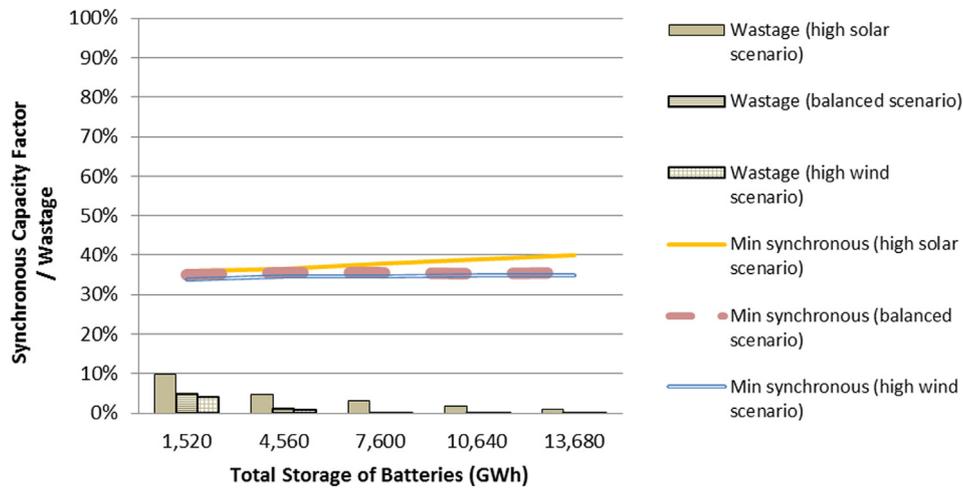


Fig. 4. Average synchronous capacity and electricity wastage as a percentage of production for energy demand scenario A. The minimum synchronous generation that would be achieved if all renewable energy resource turbines were run in “synchronous condenser mode” is also shown.

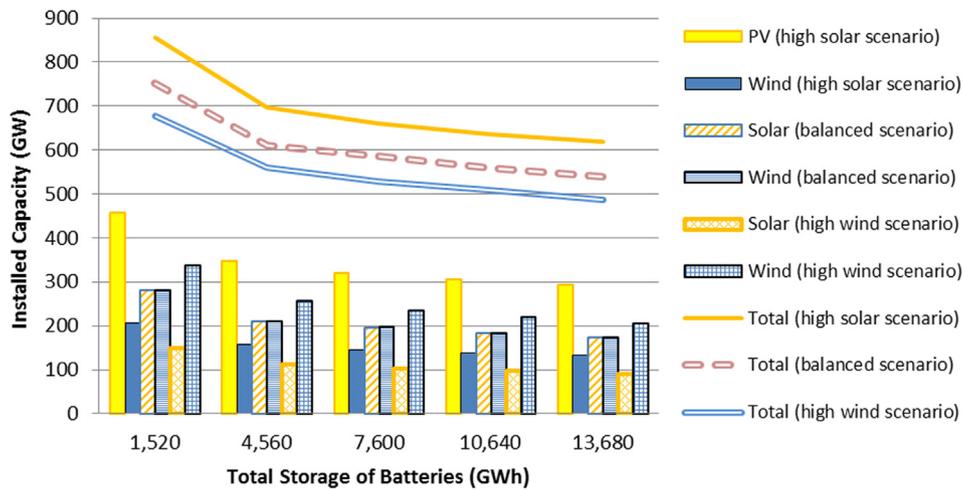


Fig. 5. Required solar and wind installed capacity for energy demand scenario B (full electrification of transport system), for different storage capacities.

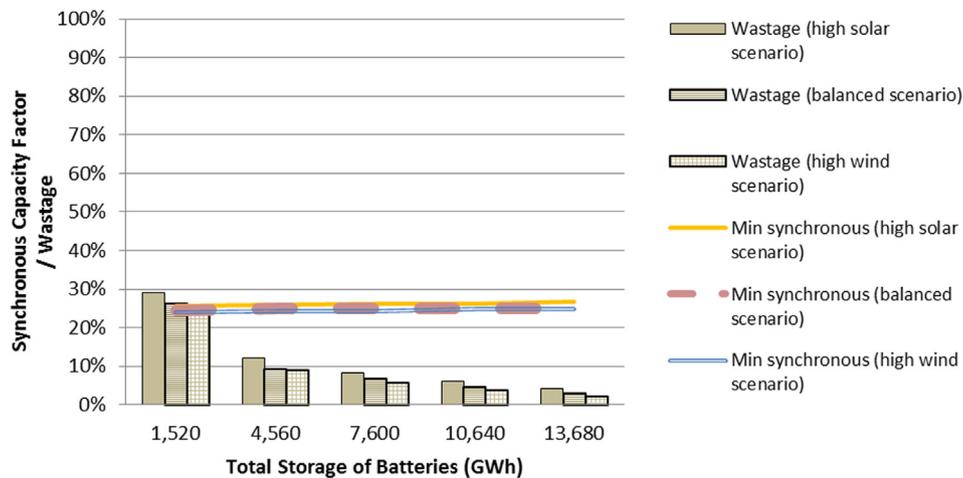


Fig. 6. Average synchronous capacity and electricity wastage as a percentage of production for energy demand scenario B. The minimum synchronous generation that would be achieved if all renewable energy resource turbines were run in “synchronous condenser mode” is also shown.

would raise from 990 TWh in 2005 to 1400 TWh in 2030. For this scenario, it is clear that a significant amount of batteries would be needed, or otherwise a completely unrealistic amount of installed wind and solar PV capacity would be required (see Fig. 9), and wastage

would become a significant problem (Fig. 10). For the highest battery storage scenario considered, the high solar scenario would require 787 GW of solar PV (almost 8 times that currently installed or in planning), and 358 GW of wind (which is around 2 orders of magnitude

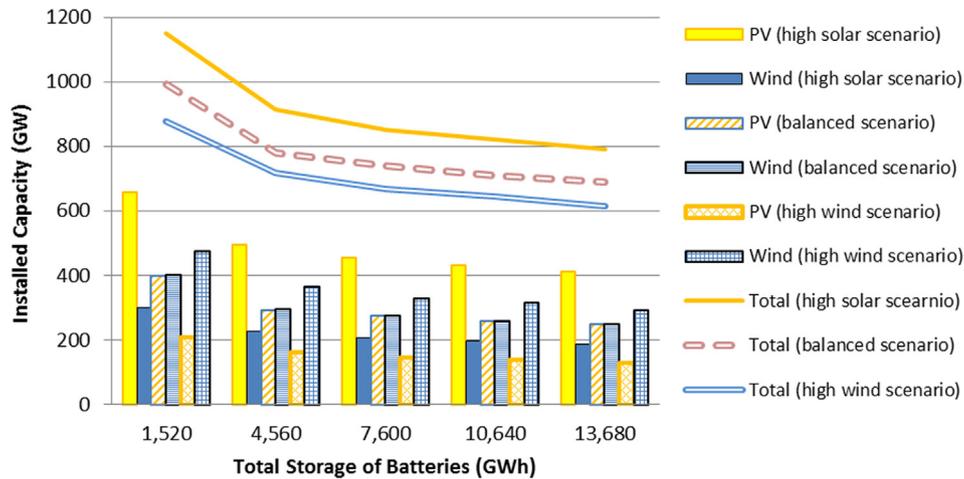


Fig. 7. Required solar and wind installed capacity for scenario C (present day electricity consumption levels), for different storage capacities.

higher than that currently installed). Clearly, the challenge in implementing such a system would lie in the feasibility of the wind power component, which would hinge on whether floating wind turbines and more powerful turbines can be developed. Current developments in the field indicate that this is unlikely to be a problem, though it appears likely that the implementation of the solar requirements of the system would come about earlier than wind. Nevertheless, even considering a high amount of batteries, wastage is likely to become a significant problem (accounting for around 20% of the electricity generated, depending on the scenario and amount of batteries), with average synchronous capacity at only around 20% and minimum around 15%. Such scenarios would clearly mean that significant changes would have to be made to the grid distribution and consumption system, requiring the use of smart grid technologies.

6. Overcoming wastage and synchronous generation issues

There are a number of alternative storage technologies that could be explored for further cost-reduction on the production side or further expansion of variable renewable energy technologies. Some of these technologies are grid-scale, such as pumped hydro power, but this is considered to be at or close to its practical limit in Japan at present. One widely considered alternative technology is hydrogen – which can also potentially compete with electric vehicles as part of the transportation fleet. Hydrogen has the advantage of being a non-carbon energy carrier that can be produced from electrolysis of water or steam reforming

from natural gas, coal or biomass resources, and can be used as longer-term or seasonal storage (in comparison to batteries which tend to be utilised for operations requiring a shorter storage period). Japan has a significant long-term government-led industrial development program for hydrogen, with major automotive, energy and industrial manufacturers being involved [51–53]. Hydrogen has been widely examined as a method to smoothen the variability of intermittent renewables [54–55], and its flexibility for stationary and mobile applications, as well as the diversity of sources, has been seen as attractive.

There are a number of major challenges to hydrogen for balancing energy supply and demand. One of the key barriers is the round-trip efficiency of electrolysis, storage and utilisation of hydrogen – for example, standard alkaline electrolysis has an efficiency of around 80%, storage requires different energy inputs depending on the type of hydrogen storage, then the re-conversion of hydrogen to electricity through a high efficiency fuel cell is around 60% efficient at best – even neglecting the storage, this is an efficiency of less than 50%. Compare this to pumped hydro (80–90% for the pumping then ~95% for generation) or 70–80% for a round-trip in batteries (potentially greater than 90% for Li-ion chemistries [56] or around 70–80% for lead acid batteries [57]). So while hydrogen may be useful for long-term storage, there are other technologies that will be more efficient in many cases. The other current issue with hydrogen is the cost of all elements in the supply chain. While the price of fuel cells and electrolysers will reduce as sales volumes increase, largescale usage is currently not financially viable.

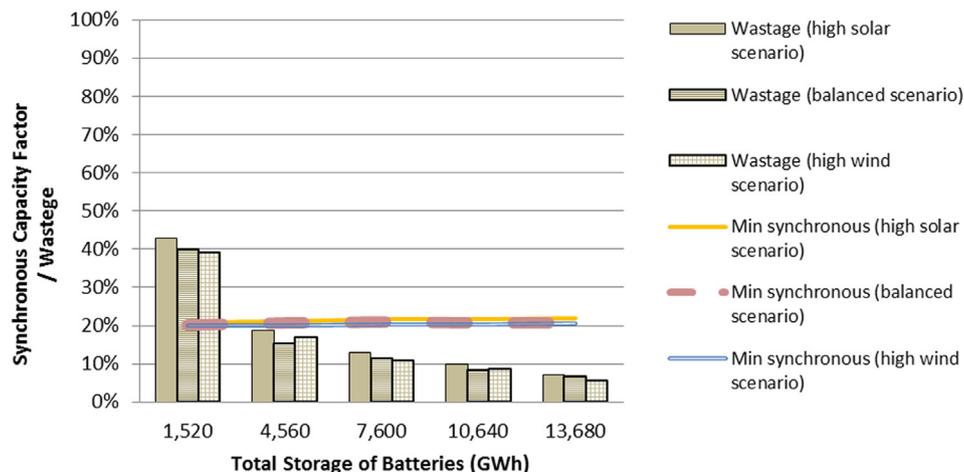


Fig. 8. Average synchronous capacity and electricity wastage as a percentage of production for energy demand scenario C. The minimum synchronous generation that would be achieved if all renewable energy resource turbines were run in “synchronous condenser mode” is also shown.

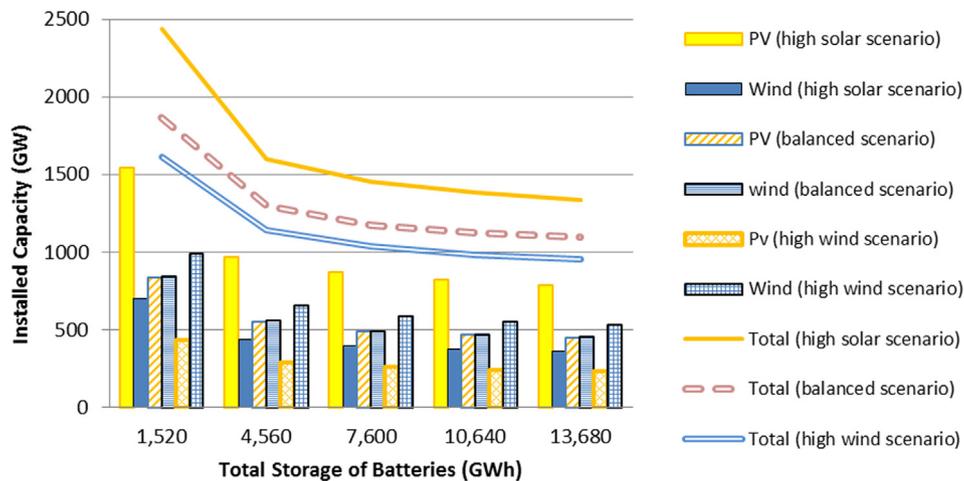


Fig. 9. Required solar and wind installed capacity for scenario D (present day electricity consumption levels), for different storage capacities.

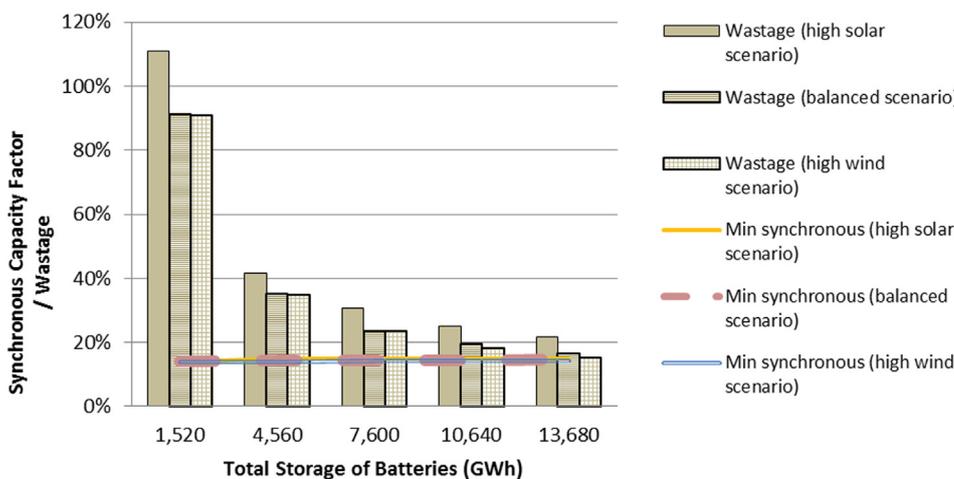


Fig. 10. Average synchronous capacity and electricity wastage as a percentage of production for energy demand scenario D. The minimum synchronous generation that would be achieved if all renewable energy resource turbines were run in “synchronous condenser mode” is also shown. In this case, wastage is greater than the amount of electricity consumed, indicating that the installed capacity is so vast that in many instances more of it will be generated that can be possibly consumed or stored (in other words, a very inefficient system).

Regarding batteries themselves, it is important to note that the required capacity in even the lowest scenarios (1500 GWh) would require an enormous increase in current mining and manufacturing capacity by 2030. While lithium ion battery production has been rapidly ramping-up, there was only around 30 GWh production capacity in 2014, with estimates that this will be around 130 GWh by 2020. At 2020 rates, this would require the whole world’s production capacity over 10 years to meet the minimum battery requirement for Japan considered here. The rates of increase in capacity show potential to keep up with demand, but it is still stretching the limits of feasibility with the proposed scenarios, in which case hydrogen as a substitute may be more attractive. In contrast, PV and wind turbines are feasible for the more modest scenarios, given that the world currently installs ~75 GW of PV panels and ~60 GW of wind turbines each year.

Currently, PV systems often operate in the maximum power tracking (MPPT) mode in order to generate the maximum amount of income, though as more renewable intermittent sources enter the grid there will be an increasing operational demand for PVs to participate in power system frequency regulation [58]. Within the framework of frequency regulation, there are typically three approaches that can be used to reduce the fluctuation in PV power output [59], including installing and operating an energy storage system (ESS) while keeping PVs in MPPT mode, installing and operating dump load banks to absorb surplus energy, or operating PV in power dispatch mode using deliberate curtailment strategies, which is probably the most cost-effective strategy. A number of authors have investigated the technical feasibility of such systems, and it appears that they are indeed possible [58–60].

Thus, it is likely that in the future PV systems will have to go from operating in the maximum power point tracking mode (maximizing their income) to also participate in power system frequency regulation. This might make these systems slightly less profitable, but as the cost of PV panels continues to decrease it is likely that such decreases in financial efficiency will quickly be overcome by technological improvements.

7. Conclusions

The present paper simulated what future 100% renewable energy scenarios might look like for the case of Japan, focusing on the feasibility of such systems and the issue of synchronous generation. The model proposed would have to be further developed and fine-tuned, but could become the backbone of a future electricity grid, by predicting (through forecasted meteorological data) the amount of electricity that would be produced throughout the year, and highlighting issues in advance of them happening.

It is clear that if significant energy savings can be made through increases in energy efficiency throughout the country, 100% renewable energy electricity mixes could be achieved. However, scenarios where electricity demand is kept constant or increase, to deal with expected increases in the uptake of electric vehicles, would pose a challenge to conventional grid systems. To overcome this it is clear that there will be a need to implement smart grid systems, make sure that there is a substantial amount of electricity batteries present, and arguably go for higher uptakes in PV power (as opposed to going for wind-intensive

scenarios, which are probably unfeasible for the case of Japan). It is also likely that such systems will require the use of hydrogen storage, so that the extra electricity produced during some times of the year can be used during the winter and summer seasons. Finally, the present simulations also highlighted that PV systems will likely have to go from operating in the maximum power point tracking mode (maximizing their income) to also participate in power system frequency regulation. This will require some adjustments, but current technology indicates that such systems are feasible.

It is worth pointing out that while the present paper was written with a Japanese perspective in mind, similar electricity grids could be achieved in other countries. Essentially, if an isolated grid can achieve a 100% penetration of renewables, other more connected grids (such as those of European countries) can succeed in smoothening intermittent energy sources through the use of interconnections, batteries and hydrogen storage.

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