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100% renewable energy in Japan

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ABSTRACT

Low-cost solar photovoltaics and wind offer a reliable and affordable pathway to deep decarbonization of energy, which accounts for three quarters of global emissions. However, large-scale deployment of solar photovoltaics and wind requires space and may be challenging for countries with dense population and high per capita energy consumption. This study investigates the future role of renewable energy in Japan as a case study. A 40-year hourly energy balance model is presented of a hypothetical 100% renewable Japanese electricity system using representative demand data and historical meteorological data. Pumped hydro energy storage, high voltage interconnection and dispatchable capacity (existing hydro and biomass and hydrogen energy produced from curtailed electricity) are included to balance variable generation and demand. Differential evolution is used to find the least-cost solution under various constraints. This study shows that Japan has 14 times more solar and offshore wind resources than needed to supply 100% renewable electricity and vast capacity for off-river pumped hydro energy storage. Assuming significant cost reductions of solar photovoltaics and offshore wind towards global norms in the coming decades driven by large-scale deployment locally and global convergence of renewable generation costs, the levelized cost of electricity is found to be US$86/Megawatt-hour for a solar-dominated system, and US$110/Megawatt-hour for a wind-dominated system. These costs can be compared with 2020 average system prices on the spot market in Japan of US$102/Megawatt-hour. Cost of balancing 100% renewable electricity in Japan ranges between US$20–27/Megawatt-hour for a range of scenarios. In summary, Japan can be self-sufficient for electricity supply at competitive costs, provided that the barriers to the mass deployment of solar photovoltaics and offshore wind in Japan are overcome.

1. Introduction

Following the recently held 2021 United Nations Climate Change Conference (COP26), 151 countries have submitted new climate plans targeting emissions in 2030 [1]. For the longer term, over 100 countries have committed to carbon neutrality by 2050–2060, including major economies such as China, the United States (US), Japan and the Europe Union [2]. Globally, the cost of solar photovoltaics (PV) and wind energy is falling and, in many places, is cheaper than the cost of electricity from new-build coal and gas power stations [3]. Solar PV and wind now account for three quarters of global net capacity additions due to their low and falling prices [4].

Low-cost solar PV and wind, when balanced by storage, transmission, and demand management, offer a reliable and affordable pathway to deep cut in emissions that is enabled by the switch to renewable energy for power generation and renewable electrification of transport, heat, and industry [4]. This pathway can be readily applied to many countries with good solar and wind resources and sufficient available land area for the deployment of solar and wind farms, such as China, the US, and Australia. However, it could be more challenging for countries such as Japan, South Korea and Germany, which have relatively small land area, dense population, and high per capita energy consumption. These countries also lack sufficient hydro resources to supply majority of their energy needs, unlike countries with low population density such as New Zealand and Iceland. In this paper the future role of renewable energy, in particular solar and wind, in these small, developed and densely populated countries, is examined from both technical and economical perspectives. This study focuses on Japan as an example.

Japan is the fifth largest greenhouse gas (GHG) emitter in the world, with low energy self-sufficiency due to the lack of conventional energy resources (coal, oil, gas). Japan currently generates 21% of its electricity from renewables, with the balance comprising nuclear (7%), fossil fuels (70%) and other (2%) [5]. The decision of the Japanese Government to commit to net-zero emissions in 2050 [6] means that large-scale decarbonization of energy needs to take place in the following

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decades. The electricity system, accounting for 42% of the total emissions in 2019 [7], is the best place to start, since decarbonized electricity can also displace oil in the land transport sector (electric vehicles) and gas in the heating sector (with assistance from heat pumps and electric furnaces).

Following Japan's prime ministerial pledge to achieve carbon neutrality by 2050, Japan's Ministry of Economy, Trade and Industry (METI) formulated a Green Growth Strategy [7] to provide a policy framework for this transition. According to this Strategy, Japan will generate 50% – 60% of its electricity from renewables by 2050, mainly from offshore wind. The rest is expected to be supplied by hydrogen (10%) and nuclear and fossil fuel power plants with carbon capture and storage (CCS) (30%–40%). In the report METI argues that 100% renewable electricity is difficult due to environmental and social constraints and concerns regarding energy flexibility, transmission, system inertia and costs. However, it is important to critically examine this argument, considering that many studies, including those presented in a recent meeting held within METI's Comprehensive Resources and Energy Study Group Basic Policy Subcommittee [8], have shown that 100% renewable electricity is technically feasible at competitive costs for many countries and regions [9].

Due to safety concerns after the Fukushima accident, a consensus has been reached in Japan that dependence on nuclear needs to be minimized [10]. CCS is still in its demonstration phase, with only 26 operating facilities globally with an annual capacity of 40 million tonnes of carbon dioxide (CO_2) [11]. It is far from ready for mass-deployment in the required timeframe to reach zero emissions in 2050 and future costs of CCS are unknown as these early-stage projects provide little information.

Japan could rely largely on imported zero-emissions energy-rich chemicals, such as ammonia produced using hydrogen derived from electrolysis powered by wind and solar in another country. However, the cost is high because the round-trip efficiency is low (~25% [12]) in converting renewable electricity to hydrogen, followed by shipment to Japan, and finally re-conversion to electricity. Green hydrogen may be beneficial when utilized occasionally to provide peaking power, but significant cost reductions would be needed for it to contribute large fractions. Decarbonizing electricity using Japanese renewable energy avoids the safety issues associated with nuclear, and effectively eliminates the need to rely on future developments and cost reductions in CCS and hydrogen technology. Relying on domestic renewable energy resources such as solar and wind also allows Japan to reduce dependence on energy imports, considering that Japan lacks fossil fuel reserves and currently imports most of its fossil and nuclear fuels [10]. Although domestic prices of solar PV and wind are currently high in Japan relative to other nations, wide deployment of solar PV and wind globally means that global cost convergence is likely to happen in the next few decades as more experience is gained and local markets become more competitive. Consequently, future costs of solar PV and wind in Japan are expected to be much lower than today's level.

Storage is essential to balance a renewable electricity system [13]. Japan had 28 Gigawatts (GW) of existing pumped hydro energy storage (PHES) installed as of 2018 [10], most of which is river-based and was built prior to the 2011 Fukushima disaster to balance generation from nuclear plants. The existing pumped hydro schemes in Japan are useful for balancing intermittent generation from solar PV and wind in a 100% renewable grid. With continued cost reductions, batteries will also play an important role in short-term supply–demand balancing and in electric vehicles. However, PHES is cheaper than batteries for overnight storage [14], which is required in a system with large fractions of solar PV. PHES can provide large-scale energy storage while batteries are well suited to provision of storage power needed for ancillary services.

Continued cost reductions and increased uptake of solar PV and wind globally have led to deliberations on the costs and feasibility of 100% renewable electricity systems in the literature in recent years [9]. However, only a few studies from academia have investigated the future role of renewable energy from Japan's perspective. Tsuchiya modelled a Japanese electricity system dominated by solar PV and wind targeting projected electricity demand in 2050, and found that the optimal system configuration would require 75% solar PV and 25% wind to minimize the required battery storage and the mismatch between generation and demand [15]. Komiyama and Fujii modelled long-term power generation mix in Japan under different nuclear and carbon regulation scenarios. They found that nuclear phase-out and 80% emission reduction by 2050 would facilitate deployment of variable renewables, with a very high cost penalty [16]. Esteban et al. modelled a PV-wind-hydro-biomass energy system in Japan and found that around 41 terawatts-hour (TWh) of storage is required to balance the variable renewable generation [17]. In a later work Esteban and Portugal-Pereira modelled a 100% renewable electricity system in Japan in 2030, and concluded that 100% renewable penetration is technically feasible for Japan [18]. The most recent work from Esteban et al. extended their prior work by investigating the transmission and provision of ancillary services in a 100% renewable Japanese electricity system [19]. They found that additional balancing mechanism would be required if future electricity demand in Japan would remain at current level or increase. From the regional level, Bogdanov and Breyer modelled a North-East Asian super grid with 100% renewable energy supply under five scenarios representing different levels of interconnection between regions [20]. They found that the 100% renewable energy system is feasible and more affordable than alternative pathways to zero emissions.

Several studies investigated the role of renewable energy in decarbonization for other densely populated and developed countries within a larger region. Kakoulaki et al. investigated the feasibility of decarbonization via green hydrogen produced from renewable electricity for the Europe Union and the United Kingdom, and found that for all analyzed countries the renewable energy potential is sufficient to meet both historical electricity demand and demand from water electrolysis [21]. Fragkos et al. investigated low-carbon pathways for eleven regions of the globe, including Japan and South Korea [22]. They found that the deployment of renewable energy in Japan and South Korea could be limited due to the use of nuclear power, leading to low economic and market potential for variable renewable energy resources in these two countries. Child et al. modelled a 100% renewable energy system in Europe under two transition pathways and found that 100% renewable energy system is technically and economically feasible for Europe and that strong interconnection would lead to lower power generation costs [23].

However, the major gap in the literature is that all studies overlooked the vast potential of off-river PHES to provide mature and low-cost storage for hours to weeks. PHES constitutes >95% of global storage energy volume and storage power for the electricity industry, and it is strange that this overwhelming storage marker leader is overlooked. It is the lowest cost, most mature and largest-scale storage technology and is capable of supporting 100% renewable electricity systems at low cost [24,25]. It can also provide ancillary services for the grid including mechanical inertia in place of retiring coal and gas power plants. Most existing PHES is associated with river-based hydroelectricity systems, which usually requires interference with rivers and can have large environmental cost and strong social pushback. Most of the existing studies applied constraints on future PHES capacity expansion due to these considerations. However, most of the world's land is not near a river, and there are many "off-river" sites. A global atlas of off-river pumped hydro energy storage identified 616,000 promising sites with combined storage of 23 million Gigawatt-hours (GWh) (an enormous amount of storage) distributed across most regions of the world [26], including 2,400 sites in Japan with a combined storage of 53,000 GWh. These off-river sites are outside protected and urban areas and are away from rivers, effectively avoiding environmental and social impacts of conventional river-based PHES.

Also, most studies assumed unlimited PV and wind potential and did not take the resource constraint into account. In fact, countries like

Japan have limited land area, and it is essential that upper bounds are established for the potential of solar PV, wind and PHES so as to establish whether the required generation and storage capacities are technically feasible. Some studies investigated mid-term solutions with coal or fossil gas in the generation mix and did not provide effective solutions to carbon neutrality. For the case of Japan, offshore wind is gaining momentum, with four offshore wind promotion zones announced by the Japanese government in 2020 [27]. However, offshore wind resources in Japan are overlooked in most studies. Additionally, all studies that investigated the role of renewable energy in decarbonization from the Japanese perspective used meteorological data from a single year or several years for modelling. However, Japan periodically experiences extreme weather [28] and models that are based on meteorological data over a short period provide limited information on the long term system performance.

In addition to the studies conducted by academics, in a recent meeting held within METI's Comprehensive Resources and Energy Study Group Basic Policy Subcommittee, several decarbonization scenario analysis pieces were presented by local organizations [8], including Renewable Energy Institute (REI), The Institute of Energy Economics Japan (IEEJ), Deloitte Tohmatsu Consulting and The Research Institute of Innovative Technology for the Earth (RITE) etc. A summary of the studies presented in this meeting is shown in Table 1.

These studies presented various pathways to energy decarbonization in Japan. However, as pointed out by METI, the pathways presented will be reviewed flexibly in the coming decades based on the progress of cost reduction and technology development, and Japan is not planning to specify a certain energy source composition in the short term, but instead is more interested in having a range of policy options available.

It is also important to point out that a wide range of values were quoted as 'upper limits' for solar PV and wind capacities in these studies. The estimated solar PV potential in Japan ranged between 350 GW and 2,746 GW among multiple studies, while that for wind ranged between 296 GW and 938 GW [8]. Most of these studies overlooked alternative types of solar PV, such as agrivoltaics (solar arrays installed on top of crops) and floating PV (solar arrays on water bodies), despite their rapid deployment globally [29,30]. In addition, offshore wind resources at deep water (>200 m) were often excluded, while projects are already being planned at locations with greater water depth [31,32], and projects with water depth up to 1000 m are technically feasible [33–35]. Therefore, there is a need for a detailed resource assessment for Japan that considers all potential sites for future solar PV and wind deployment to avoid overly conservative assumptions.

In response to the above-mentioned gaps in the literature, in this study, the future role of renewable energy in the decarbonization pathway towards carbon neutrality in Japan is thoroughly investigated, with a focus on the overwhelming generation and storage market leaders, solar PV, wind and off-river pumped hydro. A comprehensive Geographic Information System (GIS) based resource assessment is presented to identify the technical resource potential of solar PV and offshore wind in Japan. A long-term (40 years), high-resolution (hourly) energy balancing analysis is then presented of a hypothetical Japanese electricity system supplied by 100% renewable electricity, mainly solar PV and offshore wind. Hourly balancing of intermittent supply and demand is provided by pumped hydro energy storage, high voltage direct current (HVDC) and alternating current (HVAC) transmission and a small portion of other flexible energy resources (existing hydro, bio energy and green hydrogen produced from curtailed electricity).

Using Differential Evolution [36], the least-cost electricity system configurations under defined reliability, resource, energy and transmission constraints for multiple scenarios are derived. Batteries are excluded from the scope of this study due to the current high costs. However, with future cost reductions, batteries may become cheaper than pumped hydro for short-term storage, leading to lower balancing costs than the results presented. Thus, costs estimated in this study are effectively an upper bound. Onshore wind is also excluded in this study because it is not involved in Japan's current plan for carbon neutrality [7] due to lower capacity factors compared with offshore wind [37] and very limited number of available sites in Japan compared with offshore wind [38].

Historical hourly solar irradiation and wind speed data over 1980–2019 are from Japan Meteorological Agency [39] and Windatlas.xyz [40]. Hourly electricity demand data is from the Organization for Cross-Regional Coordination of Transmission Operators (OCCTO) [41]. However, demand data is available only from April 2016. In order to model 40 years of supply–demand balancing, historical demand over 2016–2019 is duplicated assuming that electricity demand and load profiles in previous years are the same as those in recent years. This assumption separates weather correlation of demand but is expected to have a neglectable impact on the results, considering that the electricity demand in Japan increased from 1980 to 2015 and has been relatively flat since then. A detailed description of the data used in this study is available in Supplementary Information A.

The current costs of solar PV and offshore wind are high in Japan. This study assumes large cost reductions for solar PV and offshore wind from the current level to global norms, which is expected to happen in the next few decades with increasing competition and more experience gained. This is different from the costs of batteries, which are currently still high in most places of the world. A detailed discussion of the cost assumptions is available in Section 2.4.

This study is an important addition to the existing 100% renewable energy studies for Japan. It introduces an alternative pathway for Japan that is built upon off-river pumped hydro for low-cost, large-scale, mature energy storage, which is yet to be well-examined in academic, business or political reports. It also presents a wide range of energy independence scenarios in which all electricity is supplied and balanced by domestic renewable energy resources, thereby avoiding energy security issues associated with energy imports.

To the best of the authors' knowledge, this is the first time that the future role and costs of a PV-Offshore Wind-Pumped-Hydro hybrid system in supplying 100% renewable energy in Japan is discussed in detail. The optimized system configurations and costs in various scenarios can be used as references by policymakers and grid operators when making decisions for the transition to a carbon neutral society. This study also contributes to the scientific community by exploring the potential role of solar PV, wind, and off-river pumped hydro in a small, developed and densely populated country. The methodologies of this study can be applied to similar countries and regions (e.g., Germany and South Korea) to estimate the domestic renewable energy potential and costs of a hypothetical 100% renewable energy system.

2. Methods

This study uses a least-cost optimization model to find the optimized electricity system configuration under specified constraints, including the resource constraint defined by the GIS-identified resource potential. This section introduces the detailed methodologies used in this study, including the optimization process, the GIS-based resource assessment, the modelling scenarios and the cost assumptions.

2.1. Optimization process to derive the least-cost solution

This study uses a modified version of the modelling framework introduced by Lu et al. [25]. The model uses time series demand and meteorological data to simulate the hourly energy balance, including demand, generation and charging/discharging of storage in each service area. The model aims at deriving the least-cost electricity system configuration under the following constraints:

- Reliability constraint: electricity generation must meet demand in every timestep unless a specified amount of deficit is allowed, to represent load shedding in certain scenarios.

- Resource constraint: installed capacity of a technology in a service area must not exceed the identified technical resource potential of this technology in this service area.
- Energy constraint: total generation from a certain technology must not exceed the specified maximum generation from this technology.
- Transmission constraint: power flow in a transmission line must not exceed the specified maximum capacity of this transmission line.

For a given set of optimization parameters (e.g. PV, wind and storage capacity in each service area) with defined upper bounds determined by the resource constraint, the model uses Differential Evolution [42] to find the parameters with which an objective function returns the lowest value. The objective function consists of the LCOE calculated based on energy balance simulations, and the penalties for not meeting the reliability, energy, or transmission constraints.

In this study, the model is modified to incorporate hydrogen as an additional dispatchable source. In a system dominated by variable renewable generation, the required storage capacity is usually driven by occasional cloudy, windless periods. Excess storage capacity is required to ride through such stressful periods but sits idle during most of the time. Additional dispatchable hydrogen could effectively mitigate this issue by providing power during these stressful periods, therefore avoiding storage overbuild and reducing the amount of storage required to cover occasional periods of low solar and wind availability. In effect, long-term storage of a modest amount of hydrogen is cheaper than construction of additional rarely-used PHES. Note that while the maximum amount of storage is defined based on the resource potential introduced in Section 3.1, there is no upper limit set for the amount of hydrogen used in the system. Hydrogen can be either imported (in the short term) or derived from water via electrolysis driven by curtailed solar and wind generation in Japan. In this study it is assumed that hydrogen is produced locally from curtailed electricity. As will be shown later in Section 3.2, the amount of curtailed electricity is far more than the optimized amount of hydrogen required. Detailed information on the algorithm and modifications of the model is available in the Supplementary Information B.

2.2. GIS-based resource assessment for solar PV and offshore wind

In order to set the resource constraints (upper bounds for the optimization parameters) in the model, the maximum capacity of PV, wind and storage in each service area need to be determined. GIS analysis is performed to estimate the technical resource potential of PV and offshore wind in each region, while data from the global atlas of off-river pumped hydro energy storage [26] is used to set the limit of pumped hydro capacity.

Four forms of solar PV deployments are considered in Japan: ground-mounted PV (GPV), building-integrated PV (BIPV), floating PV (FPV) (on rivers, reservoirs, and the inland sea) and agrivoltaics (APV) (solar array installed above crops). By incorporating land use data [43], protected area data [44], wave height data [45] and rooftop area data [46], the area available for solar PV deployment can be estimated. This is then converted to potential solar PV capacity assuming 1.5 Megawatt (MW) per hectare for ground-mounted and floating PV, 23% panel efficiency, 40%/15% utilization rate for rooftop/façade PV, and 58 Watts per square meter for agrivoltaics (average value based on existing projects in Japan [47,48]). Hourly meteorological data is downloaded for selected sites for modelling. Statistical summary of the solar PV data for each service area in Japan is presented in the Supplementary Information A.1.

For the resource potential of offshore wind, both fixed-bottom offshore wind and floating offshore wind are assessed. However, due to limited shallow water around Japan [49], the majority of the future offshore wind systems in Japan will be based on floating structures. Recent development of wind turbines with floating foundations make it possible to access far larger wind resources in water up to 1000 m deep [35]. Globally, 66 MW of floating offshore wind had been installed by 2019, of which 19 MW is in Japan [50]. Four offshore wind promotion zones were announced by the Japanese government in 2020 [27], along with the first auction for floating offshore wind farms (maximum 21 MW) in the Goto sea area [51]. Floating wind capacity is expected to increase rapidly in the next decade based on announced projects in the pipeline [52]. Rapidly increasing deployment will reduce costs to a more competitive level, which will in turn lead to wider deployment.

A scoring matrix (Table 2) is used to allocate an offshore wind suitability score for every 300 m * 300 m cell in Japan's exclusive economic zone [53]. This suitability score represents the overall suitability of installing offshore wind turbines in a certain location. In general, sites with high average wind speeds, shallow water, reasonable distance to coast and low fishing activities are preferred. Sites that are too close to the coast (<25 km) may be affected by bird activities and may have visual impacts while sites that are too far (>1000 km) would lead to high connection costs. 50–250 km is expected to be the optimal distance to the coast. Places that are within 1 km of protected areas or ferry routes and those with high fishing activities should also be avoided to minimize disruptions to the environment and commercial activities.

The total score for each cell is then calculated by:

$$\begin{aligned}\text{Total score} = \big(&\text{wind\_speed\_score} \times 50\% + \text{sea\_depth\_score} \times 30\% \\ &+ \text{distance\_to\_coast\_score} \times 10\% \\ &+ \text{fishing\_hour\_score} \times 10\%\big) \times \text{protected\_area\_score} \times \text{ferry\_route\_score}\end{aligned} \tag{1}$$

Indicative sites with above-average scores are selected for each service area for data download and modelling. Detailed information is available in the Supplementary Information A.2.

The overall GIS analysis process is summarized in Fig. 1.

2.3. Modelling scenarios

In this study an interconnected Japanese electricity system in which solar PV and offshore wind supply most energy, and dispatchable generation sources (existing hydro, existing bio energy, and new hydrogen) and pumped hydro energy storage provide the balance is modelled. While generation from solar PV and offshore wind is modelled based on historical meteorological data, as introduced in Supplementary Information B, the model uses the 'Dispatch' module to dispatch flexible generation from hydro, bio and hydrogen to stressful periods with low solar and wind availability. In every hour, the 'netload' is calculated by subtracting total generation from solar PV, offshore wind, hydro, bio and hydrogen from the demand. Storage is charged when the netload is negative (excess electricity available) and is discharged when the netload is positive (insufficient generation), therefore shifting the variable generation to meet the demand in every hour.

In the electricity system modelled in this study, the ten service areas in Japan are connected by high-voltage transmission lines to allow spatial shift of energy between regions (Fig. 2), with the costs for installing these high-voltage transmission lines included in the cost of electricity. Costs for connecting the solar and offshore wind farms are also included, assuming that solar and offshore wind farms are on average 10 km and 100 km away from the transmission network, respectively. Cost of electricity distribution within each service area is not included in this study because this study models wholesale rather than retail electricity price. The latter includes additional costs such as costs of the low-voltage distribution network and retailer services, which are out of the scope of this study.

The following primary scenarios are modelled in this study. These scenarios deal with the two most critical considerations in terms of the system configuration: whether hydrogen is included in the generation mix and whether there is a limit for solar PV due to land constraints.

1. **Baseline**: electricity is supplied by solar PV, wind, hydro, biomass and hydrogen. Existing hydro and biomass capacities are used with no further expansion. A small amount of hydro (1,631 MW or 6% of

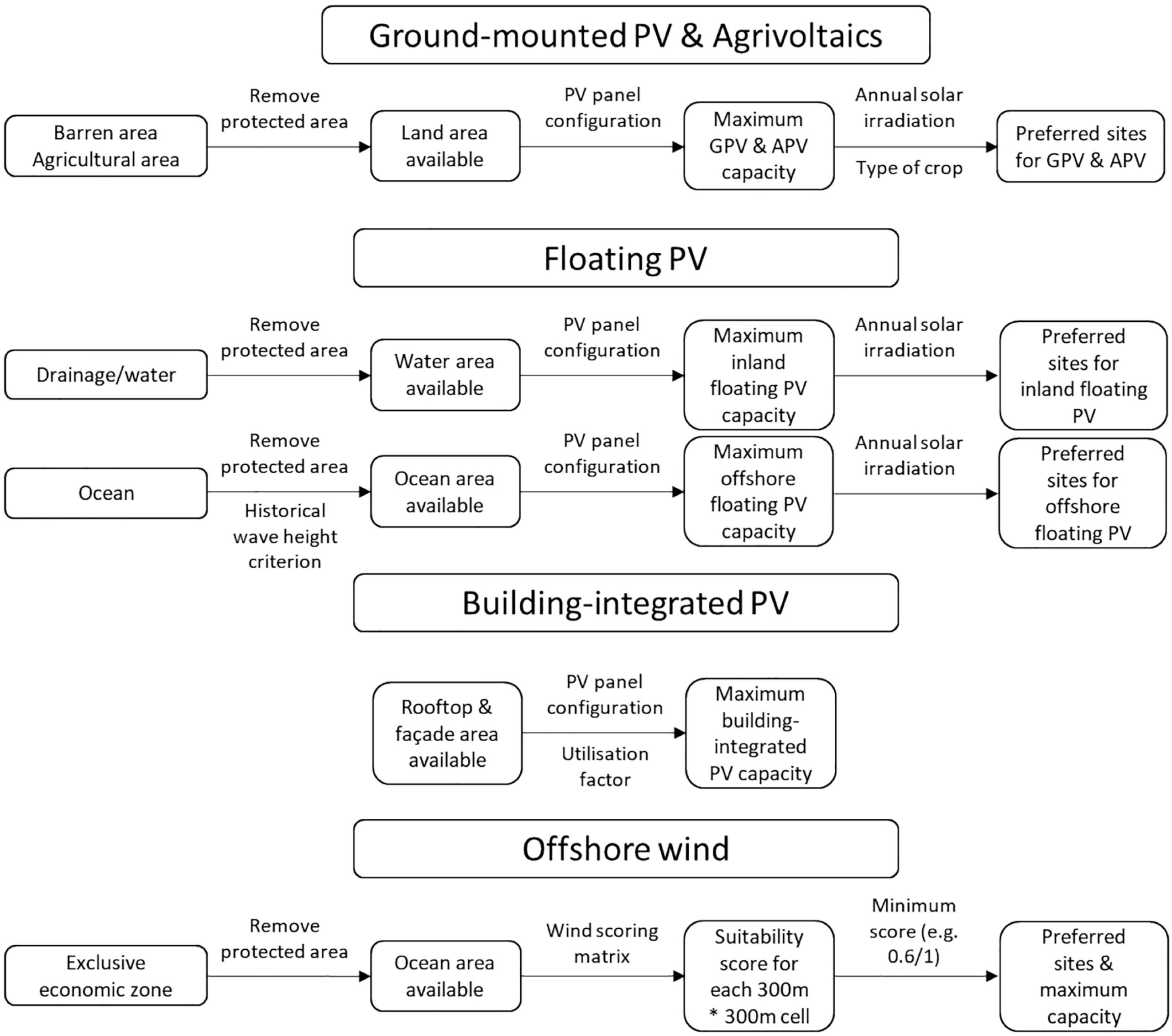

Fig. 1. GIS analysis process for the resource assessment of solar PV and offshore wind.

total hydro capacity) is assumed to be baseload (constant output 24/7). This is determined by the minimum power from hydro over 2016–2019. The rest is assumed to be dispatchable. Bio energy is assumed to be entirely dispatchable as it is dominated by solid fuel in Japan, representing around 2% of the total electricity generation in 2019 [57]. Maximum annual generation from hydro and biomass is limited to 10% of annual electricity demand, which is consistent with today's level. Other renewable energy resources (e.g., geothermal) are excluded due to the limited scale of deployment. Hydrogen (green) is assumed to be fully dispatchable and is produced locally using curtailed renewable electricity with an assumed cost of US$2/kg (discussed later in Section 2.4). The high voltage transmission network A in Fig. 2 is used.

2. **Baseline – no hydrogen**: similar to the Baseline scenario except that dispatchable hydrogen is excluded.
3. **Wind-dominated**: similar to the Baseline scenario except that an additional energy constraint is applied, limiting generation from solar PV to 20% of annual electricity supply.
4. **Wind-dominated – no hydrogen**: similar to the Wind-dominated scenario except that dispatchable hydrogen is excluded.

In addition to these four primary scenarios, secondary scenarios are modelled to further investigate the system performance under various assumptions. All these scenarios except the 'Demand management' scenario are modelled twice – with and without dispatchable hydrogen.

5. **Nuclear**: nuclear added on top of the 'Baseline' and 'Baseline – no hydrogen' scenarios. Nuclear generation is assumed to be constant 24/7 baseload, supplying 20% of the electricity demand every year (179 TWh per year), which is consistent with the 2030 outlook introduced in Japan's 5th Strategic Energy Plan [58].
6. **HVDC**: similar to the 'Baseline' and 'Baseline – no hydrogen' scenarios except that high voltage transmission network B (Fig. 2) is used.
7. **Okinawa-isolated**: since Okinawa is a relatively small load center and is located away from other service areas, this scenario tests whether the connection between Okinawa and other service areas is beneficial. It is similar to the 'Baseline' and 'Baseline – no hydrogen' scenarios except that the connection between Kyushu and Okinawa in high voltage transmission network A (dashed line in Fig. 2) is removed.
8. **Demand management**: similar to the 'Baseline – no hydrogen' scenarios except that load shedding is allowed to take place during occasional critical periods with a fixed price of $200/

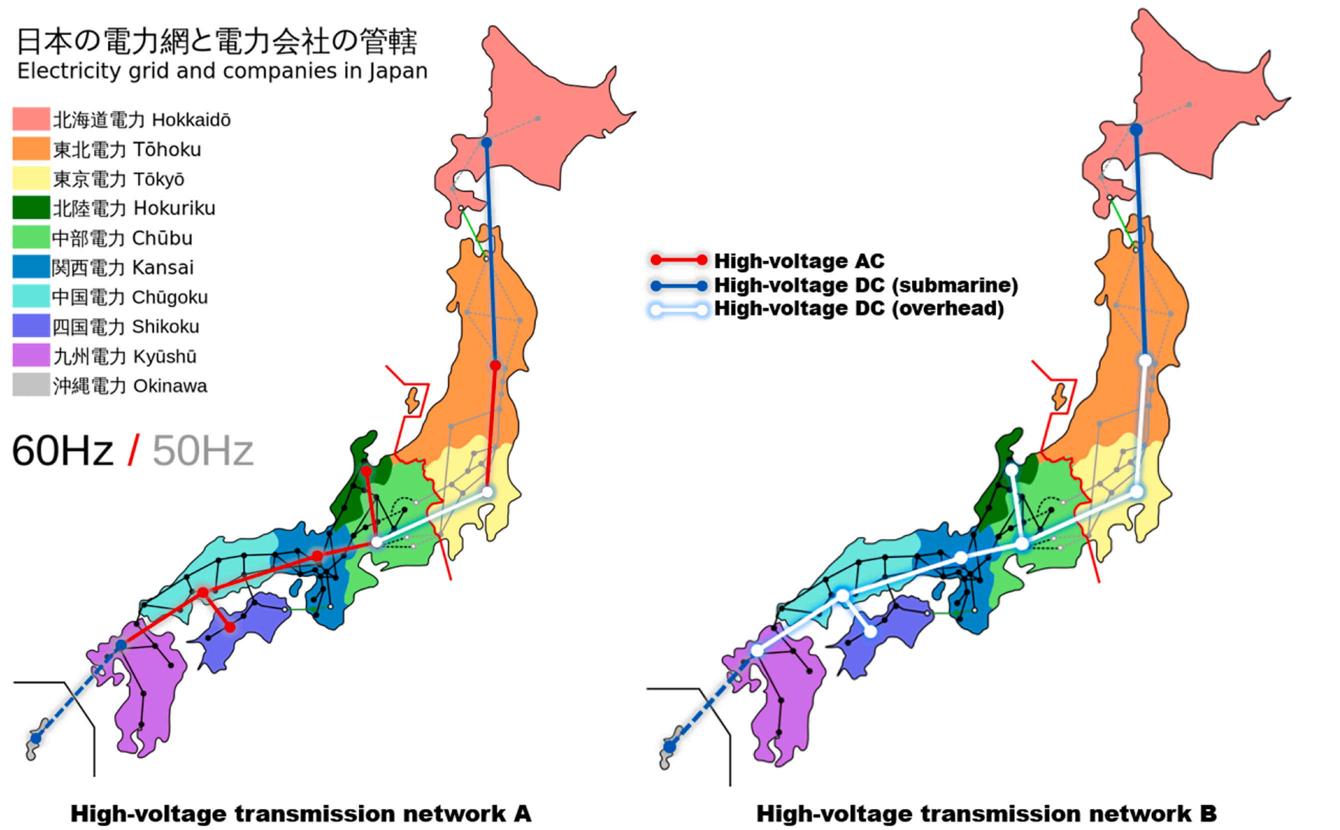

Fig. 2. Proposed high-voltage transmission network in Japan. In both networks Hokkaido-Tohoku and Kyushu-Okinawa are connected via HVDC submarine cables, and Tokyo-Chubu is connected via HVDC overhead lines due to the difference in frequencies between the two regions. In network A all other service areas are connected via HVAC lines, while in network B they are connected via HVDC overhead lines. The dashed line between Okinawa and Kyushu means in certain scenarios (Okinawa-isolated) this line is removed. Background image credit: Callum Aitchison [56].

MWh. Load shedding can be achieved by customers incentivized to reduce their electricity usage during peak hours, or more commonly, large industry users being paid to curtail production during a period of low solar and wind. Demand management is not modelled on top of the 'Baseline' scenario because it has similar role in the system as hydrogen, with costs being the only difference.

9. **Current costs**: similar to the 'Baseline' and 'Baseline – no hydrogen' scenarios except that current costs of solar PV and wind (introduced in Section 2.4) are used.

Table 1
Summary of decarbonization scenario analysis presented in the METI meeting. Information sourced from METI website [8].

Organization	RITE	REI	Deloitte	IEEJ
Model objective	Least-cost	Least-cost	Least-cost	Least-cost
Electricity demand	1,100 TWh	1,470 TWh	1,450 TWh	1,200 TWh
Generation mix	100% renewables (Detailed installed capacity not provided)	100% renewables, including 8% import: • 524 GW solar PV • 63 GW GW offshore wind • 88 GW onshore wind • 22 GW hydropower • 6 GW bio & geothermal • 20 GW import	• 95% renewables • 2% nuclear • 3% CCS (Detailed installed capacity not provided)	100% renewables(Detailed installed capacity not provided)
Storage	• 3,980 GWh batteries • 570 GW system enhancement	• 42 GW/178 GWh utility battery • 45 GW/276 GWh household battery • 30 GW/180 GWh Vehicle-to-grid (V2G) • 30 GW/180 GWh PHES • 82 GW interconnection • 20 GW international connection • 73 GW electrolyser	• 44 GWh battery • 945 GW system enhancement • 129 TWh V2G	• 398 GWh battery • 3,434 GWh compressed hydrogen storage • 468 GWh V2G • 64.4 GW system enhancement
Levelized cost of electricity (LCOE)	US$165/Megawatt-hours (MWh)	US$84/MWh	US$174/MWh	US$247/MWh

10. **100% energy**: doubling of the electricity demand in the 'Baseline' and 'Baseline – no hydrogen' scenarios to account for additional demand from other energy sectors. Electricity demand in Japan is expected to increase by 33% − 63% due to electrified transport, heat and industry, according to the studies presented in Table 1. Doubling of the demand introduces an upper bound that accounts for additional demand from aviation, shipping and the chemical industry. It would require additional renewable energy resources and would result in higher cost of electricity because existing hydro and biomass are diluted. Combined load profile is assumed to be the same as the current load profile. Load shifting could be enabled by smart charging of electric vehicles and **time-of-use (TOU)** tariffs for hot water heating with hot water tanks. These demand management mechanisms can shift the demand to match variable generation from renewables and will result in lower costs of electricity. However, these demand management strategies are not considered in this study with the aim of presenting a reliable upper bound of the costs.

2.4. Cost assumptions

The costs presented in this study are in US dollars with an exchange rate of 1 USD = 110 JPY.

The current costs of solar PV and offshore wind in Japan are high compared to global average. According to the International Renewable Energy Agency (IRENA) [59], costs of large-scale solar PV and offshore wind in 2020 were US$132/MWh and US$200/MWh in Japan, which were 132% and 138% higher than the global weighted-average LCOE for large-scale solar PV and offshore wind, respectively. Floating offshore wind, due to the additional costs for the floating structure, is more expensive and estimated to cost US$363/MWh in Japan [60], compared to US$160/MWh globally [61]. The largest reason for the unreasonably high solar and wind costs in Japan is the relative lack of economy of scale and industrial competence [62]. Historically, solar and wind developers in Japan would usually face resistance from grid owners, authorities, and landowners, and in the past have been suffering from the additional costs required to overcome these barriers. This in turn hindered the deployment of solar and wind in Japan, limiting the potential for large cost reductions from continued learning and practicing. In the meantime, in other markets such as Europe, China, and Australia, large cost reductions of solar and wind were achieved along with improving developer experience and economy of scale.

However, many experts expect Japan to close the gap with global leaders in terms of renewable energy costs, especially with its commitment to carbon neutrality removing barriers and increasing competition from global manufacturers. For example, REI estimated the LCOE for solar PV in Japan to be US$49–51/MWh by 2030, due to improvements in module efficiency and productivity, lower wafer thickness, and lower costs for raw materials and manufacturing due to market expansion [63]. Japan Photovoltaic Energy Association (JPEA) estimated a slightly higher cost of US$64/MWh (also by 2030), while pointing out that land and grid constraints need to be eliminated and appropriate incentives for renewable energy deployment would be needed for further cost reductions [64]. In fact, there has already been a steady reduction in the capital costs of solar PV in Japan over recent years (from US$3,382/kW in 2013 to US$2,300/kW in 2020), driven by the decreasing module costs globally [65].

Costs of offshore wind are primarily driven by cost of the turbine, which is less subject to local constraints and costs than onshore PV. Therefore, offshore wind costs in emerging markets (e.g., Japan) are more likely to converge to those in established markets (e.g., Europe, China) provided that the same level of industrial experience is gained through large deployment of the technology. This is consistent with the projection in the Green Growth Strategy, in which estimated offshore wind cost in Japan would be US$73–82/MWh by 2030–2035 [7]. This is close to the current cost of offshore wind globally [65]. Costs of floating offshore wind are still high even globally, as the current costs are based on a small number of early-stage demonstration projects. Many experts expect the price to drop significantly in the coming decades. For example, a study by the U.S. Department of Energy estimated the 2030 cost of floating offshore wind to be US$60–105/MWh, based on projections from various organization and expert surveys [61].

In view of Japan's determination and effort towards carbon neutrality and the expected mass deployment of solar PV and offshore wind in the coming decades, as well as the global transition to net zero, in this study significant cost reductions for solar PV and offshore wind are assumed in all but the 'Current costs' scenario. REI's estimation [63] for 2030 solar PV capital (CAPEX) and operating (OPEX) expenditures in its 'global convergence' scenario and National Maritime Research Institute's estimation [60] for the CAPEX and OPEX of future floating offshore wind in Japan are used. These costs translate to an LCOE of US $50/MWh for solar PV assuming 12% capacity factor, and an LCOE of US$82/MWh for floating offshore wind assuming 45% capacity factor. Note that the above LCOE values are indicative only as in the modelling, CAPEX and OPEX are fixed while LCOE would vary among locations depending on the local resources. Also, as will be shown later in this study, the majority of the identified offshore wind potential in Japan would require floating structures due to limited shallow water in Japan's exclusive economic zone. Although fixed-bottom offshore wind is cheaper, costs of floating offshore wind would better represent costs of future offshore wind farms in Japan.

Cost of green hydrogen is assumed to be US$2/kg. This cost includes costs of the electrolyser and hydrogen storage, but excludes cost of the electricity that is fed into the electrolyser, which is already taken into account when calculating the system LCOE. It is also assumed that hydrogen will be converted to electricity via gas peaker, and cost assumptions (average of 'low' and 'high' cases) in Lazard's report [66] are adopted in this study, with the fuel price substituted by the price of hydrogen. The cost of the gas peaker is calculated separately and is not included in the assumed cost of hydrogen (US$2/kg). The assumed cost of hydrogen is consistent with the goal set in the Green Growth Strategy, in which cost of hydrogen is expected to be below 30 yen/Nm3 (US$3/kg) by 2030 and below 20 yen/ Nm3 (US$2/kg) by 2050 [7], although these costs include cost of the electricity required for water electrolysis. The assumed hydrogen production cost of US$2/kg corresponds to US $108/MWh using 0.05427 as the kgH2/kWh conversion efficiency as quoted in Australia's National Hydrogen Roadmap [67]. The assumption for the cost of hydrogen is further validated in Section 4.2 using modelling results.

The cost assumptions used in this study are summarized in Table 3. Additional discussions of the cost assumptions adopted in this study are available in the Supplementary Information C.

Table 2
Offshore wind scoring matrix.

Constraint	Score	Weighting
Wind speed (150 m) [54]	0 at 6 m/s or lower, 1 at 9 m/s or higher; cubic relationship	50%
Sea depth [49]	0 at 1000 m or deeper, 1 at 100 m or shallower; linear relationship	30%
Distance to coast [43]	0 if distance < 25 km or > 1000 km, 0 – 1 from 25 km to 100 km, 1 – 0 from 100 km to 1000 km; linear relationship	10%
Fishing hour (annual) [55]	0 for 200 h per year or higher, 1 for 10 h or lower; linear relationship	10%
Protected area [44]	0 if within 1 km of a protected area, otherwise 1	N/a
Ferry route [43]	0 if within 1 km of a ferry route, otherwise 1	N/a

3. Results

The modelling results are summarized in this section, including the technical resource potential of solar PV, offshore wind and off-river

Table 3
Cost assumptions.

	CAPEX	Fixed OPEX	Variable OPEX	Purchase price	Lifetime (years)	LCOE
Solar PV current	$2,300/kW	$49/kW p.a.	–	–	25	$132/MWh
Solar PV future	$585/kW	$17/kW p.a.			25	$50/MWh
Floating offshore wind current	$13,636/kW	$614/kW p.a.	–	–	25	$363/MWh
Floating offshore wind future	$3,100/kW	$136/kW p.a.			25	$82/MWh
Pumped hydro energy storage	$530/kW$47/kWh [a]	$8/kW p.a. $112,000 at year 20 and 40	$0.3/MWh	–	60	–
HVDC overhead	$224/MW-km $112,000/MW [b]	$2.24/MW-km p.a. $1,120/MW p.a. [b]	–	–	30, 50[b]	–
HVDC submarine	$2,000/MW-km [c]	$20/MW-km p.a. [c]	–	–	30	–
HVAC	$1,050/MW-km [d]	$10.5/MW-km p.a. [d]	–	–	50	–
Existing hydro and other renewables	–	–	–	$100/MWh	–	–
Existing nuclear	–	–	–	$94/MWh	–	–
Hydrogen via Gas Peaker	$813/kW	$15/kW p.a.	$5/MWh	$108/MWh[e]	20	–
Real discount rate		3.5%				

Notes:
[a] US$530/kW for power components (turbines, generators, pipes, transformers etc.), US$47/kWh for energy components (dams, reservoirs, water etc.).
[b] $/MW-km for transmission lines (50 years); $/MW for a converter station (30 years).
[c] Including transmission lines and converter stations.
[d] Including transmission lines and substations.
[e] US$108/MWh correspond to US$2/kg.

PHES in Japan, the optimized system configurations and costs, and a sensitivity analysis.

3.1. Technical resource potential of solar PV, offshore wind and off-river PHES in Japan

A total of 4,117 GW of solar PV potential has been identified using GIS analysis, comprising ground-mounted PV (3 GW), building-mounted PV (101 GW), floating PV on inland rivers, lakes and reservoirs (376 GW), floating PV on the Japanese inland sea (234 GW) and agrivoltaics (3,402 GW). The distribution of the identified solar PV potential by service area is shown in Fig. 3.

Assuming an average capacity factor of 12% [68], the technical resource potential of solar PV in Japan represents an annual electricity generation of 4,328 TWh, which is nearly 5 times Japan's current electricity demand. Note that this assumes 100% utilization of the available land, water and agricultural area. The realistic potential of solar PV is substantially lower, because competition from other land- or water-use activities will challenge a significant fraction of the identified agrivoltaics and floating PV potential. However, the high technical resource potential identified means that only 20% of the available areas need to be utilized for solar PV by itself to still supply 100% electricity demand in Japan.

A vast offshore wind resource in Japan is identified. An Offshore Wind Score Map representing the relative suitability of offshore wind deployment is shown in Fig. 4. Each 300 m * 300 m area in Japan's exclusive economic zone is scored in the range of 0–1 based on the local wind resource, ocean depth, distance to coast, fishing activities, protected areas and ferry routes.

The estimated technical resource potential of offshore wind in Japan depends on the specified minimum score, as shown in Fig. 5. An indicative wind farm with a minimum score of 0.6 is 30 km away from coast and has an annual mean wind speed of 7.5 m/s at 150 m hub height and a sea depth of 100 m. This represents a typical cost-effective offshore wind site and a large area of the four offshore wind promotion zones in Japan [27] falls in this category. The sites that score higher than 0.6 represent a total offshore wind potential of 2,138 GW assuming area requirement of 5 MW/km^2, or 8,428 TWh annual electricity generation assuming an average capacity factor of 45% [37]. The potential capacity in each service area with a minimum score of 0.6 is shown in Fig. 6.

Most of the areas with a score higher than 0.6 require floating structure. Fixed-bottom offshore wind represents <1% of the identified 8,428 TWh offshore wind potential in Japan, assuming a maximum water depth of 50 m, and around 2% of the identified potential with a maximum water depth of 75 m.

Many of the previous studies that attempted to investigate the

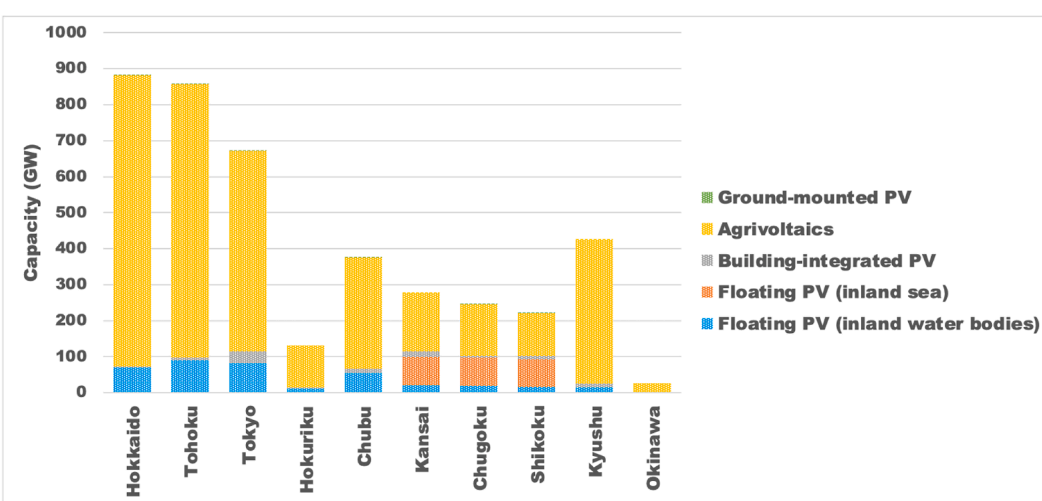

Fig. 3. Identified solar PV potential by service area. Assuming 100% utilization of the available land, water and agricultural area.

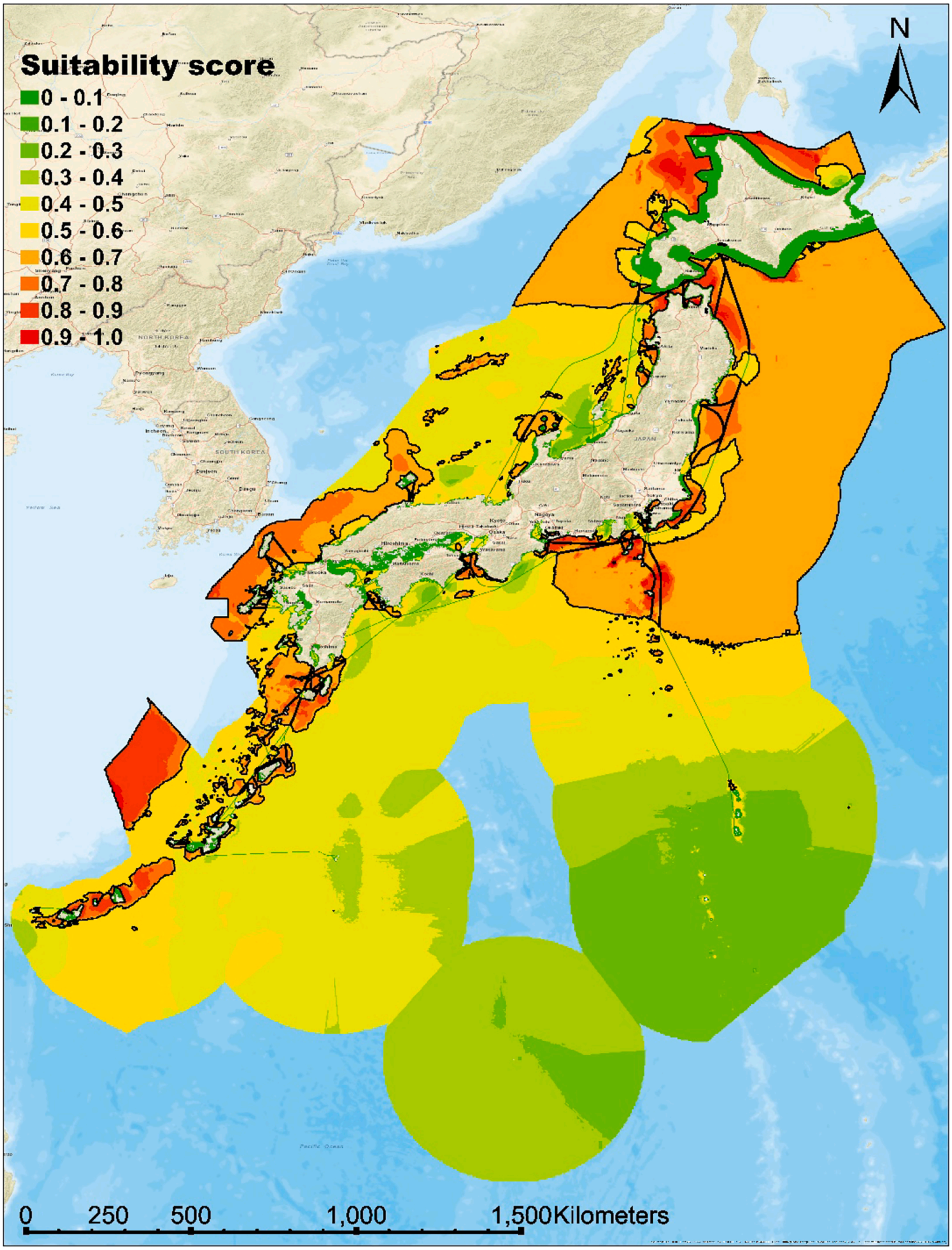

Fig. 4. Offshore wind score map. Extent: Japan's exclusive economic zone. Area enclosed by the black line represents preferable wind sites that has a suitability score above 0.6. Resolution: 300 m*300 m. Basemap credit: Esri, USGS | Esri, HERE, Garmin, FAO, NOAA, USGS.

offshore wind potential in Japan limited the maximum sea depth to 200 m [69–71]. However, as mentioned earlier, floating offshore wind projects are already being planned at deeper water [31,32], and projects with water depth up to 1000 m is technically feasible [33–35]. Excluding deep water would severely underestimate the offshore wind potential in Japan, as most of Japan's exclusive economic zone is in deep water. This study avoids such issues by incorporating all factors that affect the costs of the wind farms (e.g., wind speed, sea depth, distance to coast) and calculating the overall cost-effectiveness for each potential site.

A global atlas of off-river pumped hydro was developed by Stocks et al. [26]. It identifies 2,400 potential off-river pumped hydro sites in Japan with a combined storage potential of 53,000 GWh. All sites are outside protected areas. The distribution of the identified sites in Japan and 3D visualization of a sample site located in Chubu is shown in Fig. 7. The identified pumped hydro energy storage potential is enormous and

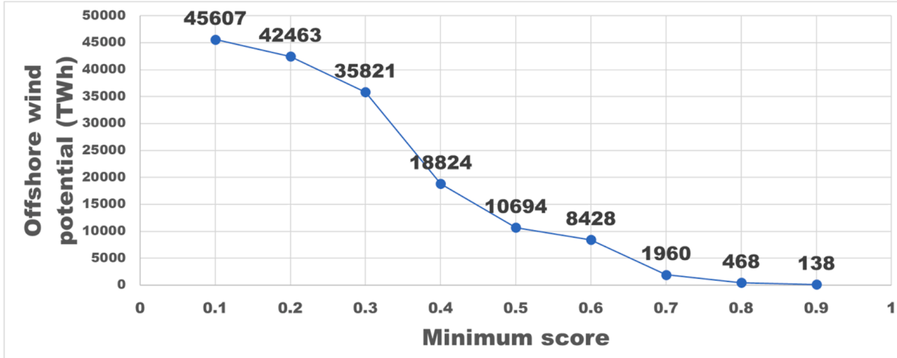

Fig. 5. Relationship between offshore wind potential in Japan and minimum score.

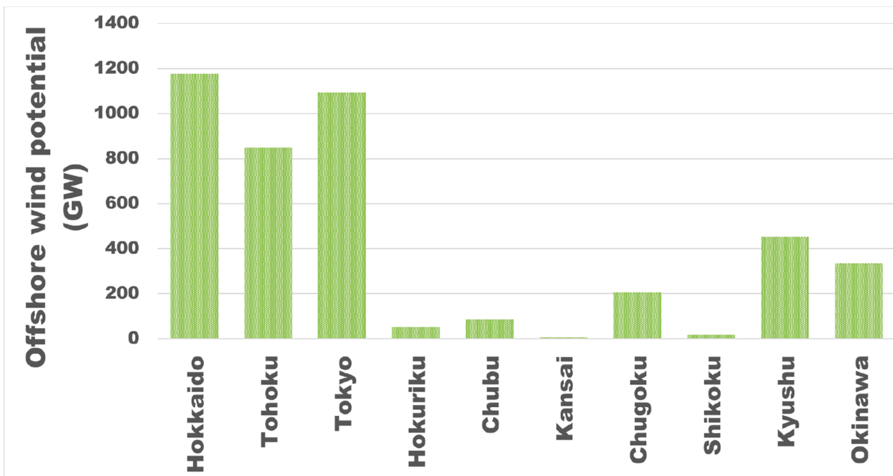

Fig. 6. Identified offshore wind potential by service area with a minimum score of 0.6.

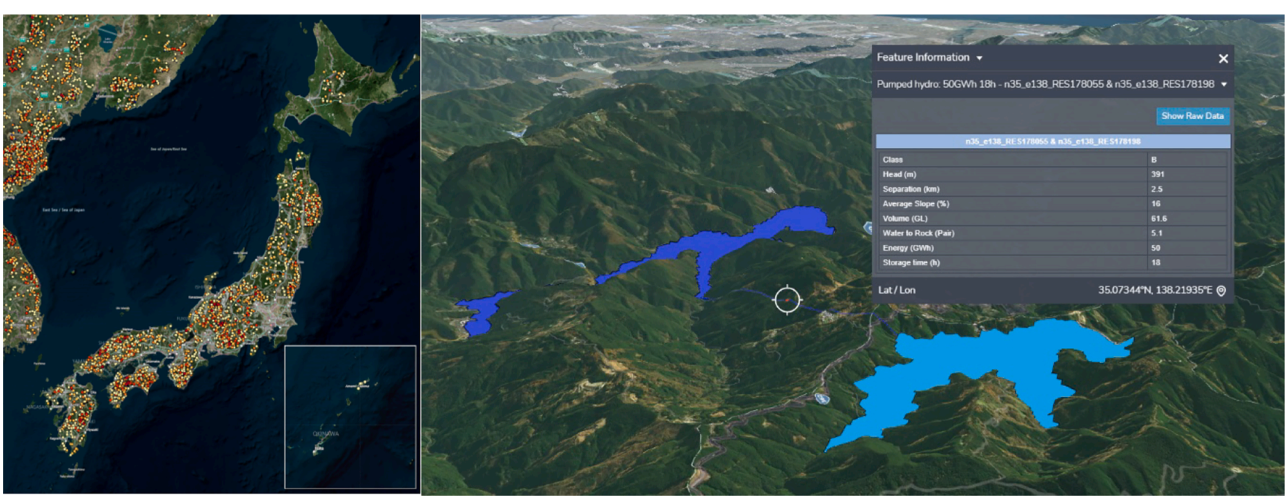

Fig. 7. Distribution of off-river pumped hydro sites in Japan (left) and 3D visualization of a sample site in Chubu (right). Image from Australian Renewable Energy Mapping Infrastructure [72] and original data from the Australian National University Global Pumped Hydro Atlas [26].

widely distributed in most service areas except Hokkaido and Okinawa, in which only 855 GWh and 20 GWh of storage is found respectively.

3.2. *Optimized configurations and costs of the proposed electricity system*

3.2.1. *Primary scenarios – Hydrogen and wind*

Breakdown of LCOE, generation mix, and storage requirements for the four primary scenarios are shown in Fig. 8. Detailed explanations of the scenarios can be found in Section 2.3.

LCOE ranges from US$86/MWh in the 'Baseline' scenario to US $139/MWh in the 'Wind-dominated – no hydrogen' scenario. In the two baseline scenarios solar PV is expected to supply the majority of the electricity demand, due to its lower costs. Limiting the contribution from solar PV will lead to significant increase in LCOE, as offshore wind

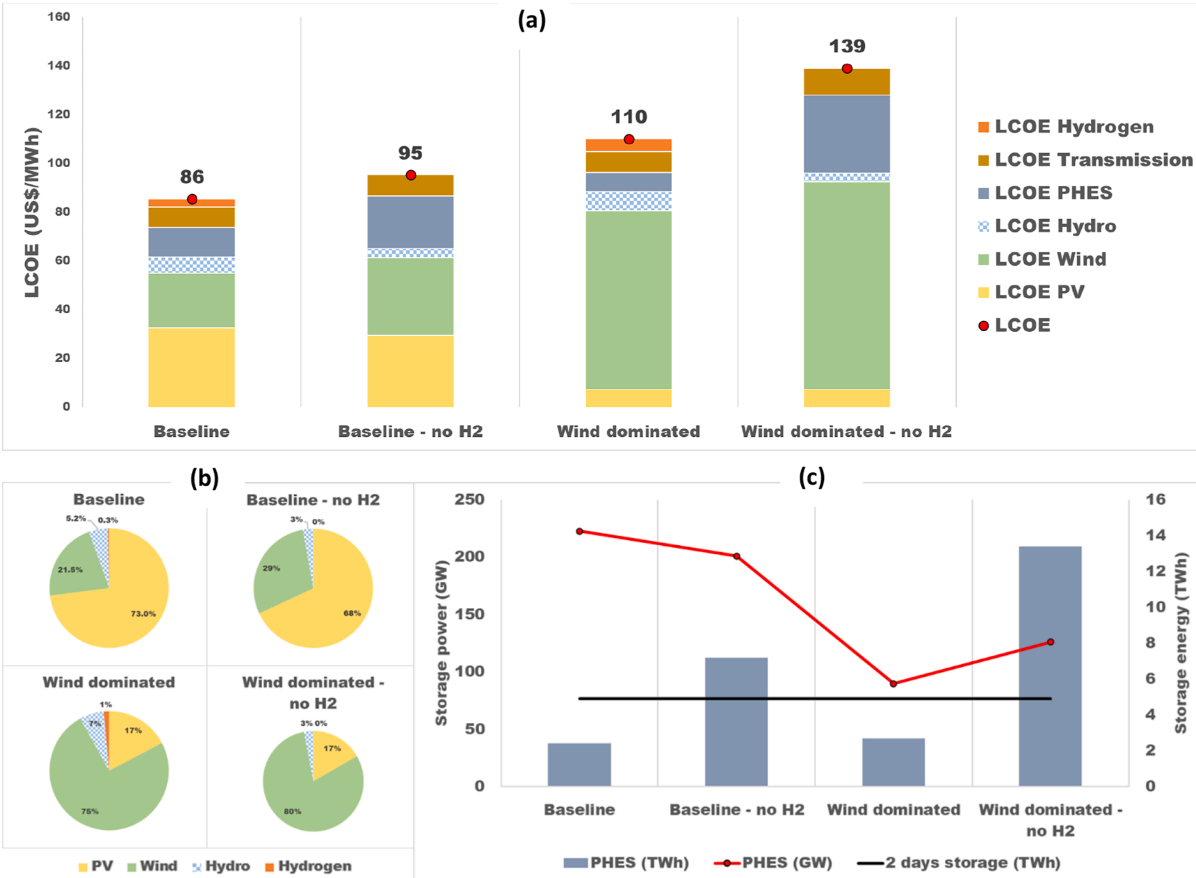

Fig. 8. Breakdown of LCOE (a), generation mix (b) and storage requirements (c) for the 4 primary scenarios. 'Hydro' refers to hydro plus biomass for simplicity. In (c) '2 days storage' represents the amount of storage that is equivalent to average electricity demand over a 2-day period (approximately 5 TWh) for comparison.

generation is expected to cost 50% more per MWh than solar PV. It also leads to higher storage energy (TWh) but lower storage power (GW). This is because wind is more volatile than solar in Japan, and larger storage is required to accommodate occasional windless periods. However, a PV-dominated system experiences daily cycles and requires more storage power to store excess electricity generated during daytime.

Excluding dispatchable hydrogen has substantial impacts on the LCOE for both the 'Baseline' scenario and the 'Wind-dominated' scenario, even when the contribution from hydrogen is small from a total energy perspective (orange area in Fig. 8b). The small hydrogen generation is beneficial to ride through occasional cloudy, windless periods, while most of the time it is not utilized. Most of the increase in LCOE comes from the increase in storage requirement, with the PHES component of LCOE increased by US$9/MWh for the 'Baseline' scenario and US$24/MWh for the 'Wind-dominated' scenario. This increased storage is rarely used, and it is lower cost to have hydrogen-burning generators on standby. Removing hydrogen leads to higher contribution from wind and lower contribution from both solar PV and existing

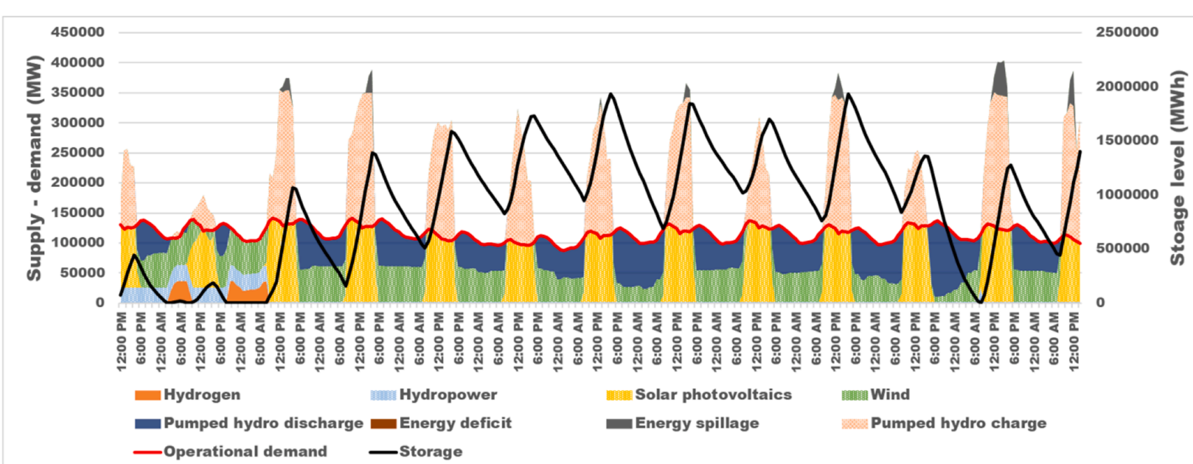

Fig. 9. Hourly load and generation profiles over typical stressful periods (1980.1.19 – 1980.2.10) for the Baseline scenario. 'Storage' refers to the state-of-charge level of the storage facilities.

hydro and biomass. This is because dispatchable generation is mostly utilized at night when solar is not available and storage is empty (Fig. 9). The absence of hydrogen therefore requires either additional wind capacity or the storage capacity or both, with the exact mix determined by the optimization. In these scenarios both wind and storage capacities are increased for the least-cost solution. The additional storage is then used in preference to hydro and biomass during periods of low generation, and therefore dispatchable hydro and biomass are needed less frequently. The lower contribution from solar PV also explains the decrease in storage power (Fig. 8c) with hydrogen removed.

3.2.2. Secondary scenarios

Breakdown of LCOE for the secondary scenarios are shown in Fig. 10 (with hydrogen) and Fig. 11 (without hydrogen). The two baseline scenarios are also presented for comparison.

In both cases switching HVAC connections to HVDC yields the same results. Removing the connection between Okinawa and other regions leads to higher costs when no hydrogen is available, because the PHES resource in Okinawa is limited (only 20 GWh available) and therefore PV and wind need to be greatly overbuilt to meet the demand when generation is low (e.g., nights), which increases the LCOE in Okinawa. In real world, batteries could be installed to substitute PHES and avoid such high spillage. When flexible hydrogen is included, the LCOE is reduced to the same level when energy flow from other regions is available (i.e., the baseline scenario). Supplying 20% of the electricity demand using nuclear leads to slightly lower LCOE when no hydrogen is available, because this increase in baseload lowers the needs for PV, wind and storage. However, when hydrogen is available, increased wind plus hydrogen is lower cost than nuclear. As a result, the LCOE of the 'Nuclear' scenario is slightly higher than that of the 'Baseline' scenario.

Demand management has little impact on LCOE and is rarely used. Total load shedding over 40 years is only 3,675 MWh, and during the most stressful period only 2% of the load is curtailed. This low use is due to the high price of demand management (US$200/MWh - nearly twice the cost of hydrogen). More load shedding and cost reductions may be possible if demand management can be achieved at lower prices. However, even with similar costs, demand management is unlikely to compete with hydrogen in terms of meeting demand during extended periods of low generation, because it is constrained by the number of electricity users that participate in the program and their electricity usage. For example, the average hourly load in Japan is around 100 GW, and in the 'Baseline' scenario the hydrogen capacity is 37 GW, representing nearly 40% of the load. However, curtailing 40% of the load via demand management is unrealistic.

Doubling current electricity demand increases the LCOE by US$4/MWh with hydrogen, and by US$9/MWh without hydrogen. The increase in LCOE is because existing hydro and bio energy, which provide cheap balancing of variable generation, are diluted. In the '100% Energy' scenario, the role of flexible hydro and bio energy is supplemented by hydrogen, which is more expensive. In the '100% Energy – no H2′ scenario, additional storage capacity is required to compensate for the reduction in contribution from flexible hydro and bio energy.

The cost of solar PV and wind needs to approach global norms, otherwise the LCOE is more than doubled as shown in the 'Current costs' scenario. The higher cost of solar PV and wind in Japan is largely due to the lack of competition. However, prices have started to come down in recent years with more auctions for solar and wind projects and increase competition from global manufactures, as discussed in Section 2.4.

A detailed summary of the modelling results is shown in Table 4, including storage and transmission requirements, capacity (GW) and annual generation (TWh) for each generation technology, energy spillage and costs. Breakdown of LCOE is expressed as levelized cost of generation (LCOG) (costs of solar PV, wind, nuclear, hydro and biomass) and levelized cost of balancing (LCOB), including costs of storage, transmission anddispatchable hydrogen.

3.3. Sensitivity analysis

To test the impact of uncertainties in the cost assumptions, sensitivity analysis has been performed for the 'Baseline' scenario and the 'Wind-dominated' scenario. Costs of solar PV, wind, hydro, transmission, storage, hydrogen, and discount rate are varied by ± 20%. To save computation time, only the 'worst year' is modelled in the sensitivity analysis. The 'worst year' contains the most stressful period in which solar irradiation and wind speeds are constantly low, which drives up the system costs. Details on how the 'worst year' is identified for different scenarios are available in the Supplementary Information D.

The 'worst year' is found to be 1993 for all scenarios except the two 'Wind-dominated' scenarios, for which the worst year is found to be 2006. Modelling only the worst year yields similar results compared with the full 40-year modelling for both the 'Baseline' scenario (both $86/MWh) and the 'Wind-dominated' scenario ($110/MWh vs $106/MWh), which demonstrate the effectiveness of this 'worst year' approach. The sensitivity analysis results are shown in Fig. 12. For the 'Baseline' scenario, changes in LCOE are small (≤$5/MWh) when individual cost components are varied. Wind costs, PV costs, and discount rate have larger impacts on LCOE compared with other factors.

Changes in LCOE for the 'Wind-dominated' scenario are larger, with the increase in wind costs having the largest impact on LCOE ($14/MWh). It also shows an asymmetric pattern in which increased costs have larger impacts on LCOE compared with decreased costs, especially when solar PV and hydro costs are varied. This is because in the 'Wind-dominated' scenario, contribution from solar PV and hydro is constrained. Therefore, the impediment caused by moving away from the optimized configuration cannot be offset by the benefit from increasing the reliance on the 'cost-reduced' component.

The sensitivity analysis shows that the modelled LCOE depends largely on the cost assumptions adopted in this study. Given the

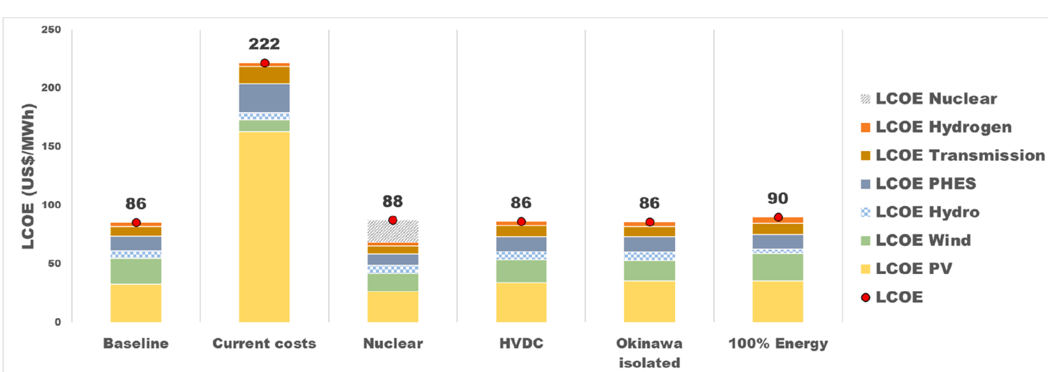

Fig. 10. Breakdown of LCOE for the secondary scenarios (with hydrogen).

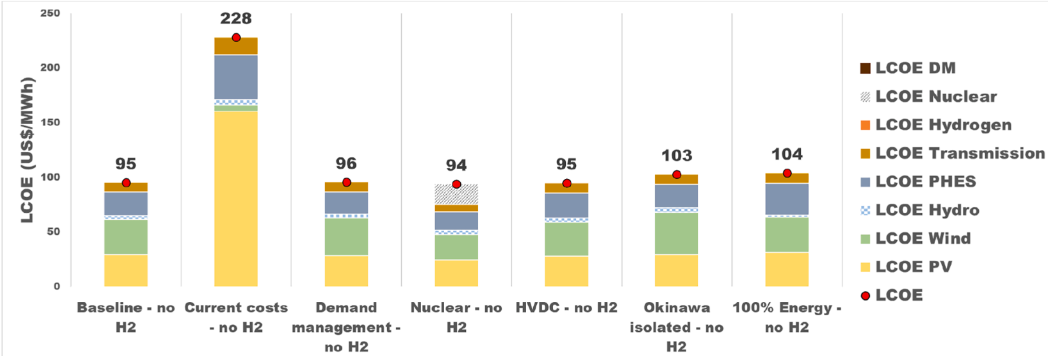

Fig. 11. Breakdown of LCOE for the secondary scenarios (without hydrogen). 'LCOE DM' represents the LCOE component due to payments for demand management.

uncertainties of future costs of generation, storage and transmission in Japan, a few dollars' difference in LCOE is within the margin of error and may have no real implications. It is therefore important to focus on the factors that have more dramatic impacts, i.e., the primary scenarios.

4. Discussion

This section discusses the implications of the modelling results, including renewable energy resources in Japan, costs of the hypothetical 100% renewable electricity system, decarbonization of other energy sectors, and implications for other similar countries and real-world applications.

4.1. Japan's renewable energy resources

In this study over 4,000 GW of solar PV potential and over 2,000 GW of offshore wind potential in Japan are identified. Combined, they represent annual generation of over 13,000 TWh, which is 14 times larger than current generation. The modelling results suggest that required PV capacity ranges from 122 GW to 1,199 GW, which is 3% – 29% of the identified potential. Required offshore wind capacity ranges from 4 GW to 232 GW, corresponding to 0.2% – 11% of the identified potential. In the 'Baseline' scenario, 549 GW of solar PV and 61 GW of wind are needed, which represent 13% and 3% of the identified potential, respectively. Note that this assumes no further expansion of existing hydro and bio capacity, and essentially all current thermal and nuclear generation are replaced by solar PV and wind. In contrast to the accepted wisdom that a maximum of 50% – 60% of the electricity demand can be realistically supplied by renewables [7], Japan has sufficient land and water area to supply its entire electricity demand with domestic renewable energy resources, mostly PV and wind. It does not have to rely on nuclear or hypothetical CCS or a large amount of imported clean electricity or fuel from other countries (e.g., hydrogen from Australia or an HVDC cable from China or Mongolia) in the transition to a carbon neutral society. The Japan Wind Power Association is proposing 30–45 GW of domestic offshore wind generation by 2040 [73]. This is more than half of the modelled wind capacity (61 GW) in the 'Baseline' scenario, although a higher capacity (87 GW) is needed in the 'Baseline – no hydrogen' scenario. Cost of offshore wind, including floating offshore wind, is expected to approach global norms in the coming decades with increased deployment and competition from global manufactures.

Even though a large technical resource potential has been identified for solar PV, as discussed earlier a significant fraction of the identified agrivoltaics and floating PV potential may not be viable due to competition from other land use activities. Experts estimated that agrivoltaics could be installed on around 10% of Japan's agricultural land [74]. Also, although such regulation does not exist in Japan, Indonesia allows only 5% of the reservoir surface to be used for floating PV [75]. Under such constraints, a rough estimation of the actual solar PV potential in Japan is around 700 GW. However, unlike PV, offshore wind turbines can effectively co-exist with other offshore activities, and therefore most of the identified offshore wind capacity is expected to be economically, environmentally and socially feasible. The 'wind-dominated' scenarios are therefore included in this study based on these considerations. The maximum required wind capacity is around 232 GW ('Wind-dominated – no hydrogen' scenario), which is only 11% of the identified wind potential. In this scenario only 123 GW of solar PV is needed, nearly half of which was already deployed by 2019 [76].

The storage requirement ranges from 2,069 GWh to 20,376 GWh, corresponding to approximately 1–8 days of consumption. This represents 4% – 38% of the identified PHES potential. Extreme (>10,000 GWh) quantities of storage are only needed when the electricity system is dominated by a single generation technology or all energy sectors are electrified but no flexible hydrogen is available. In the 'Baseline' scenario, 2,415 GWh or 19 GWh per million people of storage is needed to support 100% renewable electricity. This is consistent with the value (20 GWh per million people) for Australia reported in a previous study [24].

Large deployment of domestic renewable energy, especially offshore wind, in Japan may affect local lifestyle and fishery rights and as a result, may introduce social impacts. A detailed discussion on the potential impacts on local communities of the proposed pathway is out of the scope of this paper. However, in the transition to carbon neutrality, Japan might have to compromise and consider the tradeoff between the potential social impacts caused by domestic renewable energy deployment and the costs and energy security issues from importing expensive low carbon fuel or electricity.

4.2. Levelized cost of 100% renewable electricity in Japan

LCOE in the 'Baseline' scenario is found to be US$86/MWh, which is significantly lower than the average system prices on the spot market in Japan in 2020 (US$102/MWh [77]). Transmitting solar and wind generated electricity from Central Asia (Western China or Mongolia) to Japan via HVDC would cost about US$60/MWh assuming steady 24/7 supply, including costs of generation (US$35/MWh), costs of storage and spillage (US$18/MWh) [24] and costs of a 3000-km HVDC transmission line ($US7/MWh). State-of-the-art HVDC transmission in China operates at 1,100 kV over 3,293 km and transmits 12 GW power from Xinjiang to Anhui with 10% loss [78]. The lower cost for electricity generation and balancing is due to the lower cost for onshore wind, better solar resources, and better averaging from wide distribution of resources. This is a cheaper option but there are political barriers to overcome as this may introduce energy security issues, which contradicts Japan's '3E + S' (energy security, economic efficiency, and environment plus safety) philosophy [79]. Also, several HVDC lines with a combined capacity of 100 GW would be required if the majority of

Table 4
Summary of modelling results. Detailed explanation of the scenarios can be found in the Section 2.3. '9 Area' represents the 9 service areas other than Okinawa. 'Oki' represents Okinawa. They are modelled separately in the 'Okinawa isolated' scenario. The results are calculated by the weighted average of these two models. Pumped hydro is built to have the same power capacity for pumping and generation. 'PHES (GW)' refers to this rated power capacity. 'PHES Generation (GW)' refers to the power capacity required for generation only, which is smaller than (higher power required for pumping) or equal (lower power required for pumping) to 'PHES (GW)'.

Scenarios	Energy (TWh)	PV (GW)	PV (TWh)	Wind (GW)	Wind (TWh)	Hydro & bio (TWh)	Hydrogen (GW)	Hydrogen (TWh)	Nuclear (GW)	Nuclear (TWh)	Spillage (%)	PHES (GW)	PHES Generation (GW)	PHES (GWh)	HVDC/ HVAC (GW)	LCOE (US $/MWh)	LCOG (US $/MWh)	LCOB (US $/MWh)
Baseline	896	549	827	61	244	59	37	4	0	0	14%	223	145	2415	530	86	61	24
Baseline - no H2	896	496	763	87	326	32	0	0	0	0	14%	201	152	7180	504	95	65	30
Wind dominated	896	123	179	199	772	68	40	15	0	0	11%	90	90	2697	463	110	88	22
Wind dominated - no H2	896	123	179	232	861	32	0	0	0	0	14%	126	126	13,386	521	139	96	43
Current costs - no H2	896	749	1148	4	13	43	0	0	0	0	16%	347	151	13,750	924	228	171	57
Current costs	896	765	1146	6	22	52	38	2	0	0	18%	406	152	5053	926	222	179	43
Demand management - no H2	896	481	733	94	354	30	0	0	0	0	14%	191	151	6816	525	96	66	29
Nuclear - no H2	896	411	625	64	238	34	0	0	20	179	11%	174	124	5574	390	94	71	23
Nuclear	896	446	680	42	168	62	31	3	20	179	12%	181	125	2069	477	88	68	20
HVDC - no H2	896	478	726	83	326	36	0	0	0	0	11%	201	144	7950	493	95	63	32
HVDC	896	578	874	54	216	61	38	4	0	0	16%	233	146	2499	499	86	61	26
9 Area no H2	888	472	716	87	332	36	0	0	0	0	12%	195	142	7251	582	95	65	31
9 Area	888	592	902	46	182	65	39	5	0	0	16%	243	145	2469	557	86	60	26
Oki no H2	8	19	29	20	59	0	0	0	0	0	91%	2	1	20	0	928	910	17
Oki	8	6	9	0	0	0	1	1	0	0	12%	2	1	20	0	79	41	38
Okinawa isolated - no H2	896	491	746	107	391	36	0	0	0	0	18%	196	143	7271	582	103	72	31
Okinawa isolated	896	598	911	46	182	65	40	6	0	0	16%	246	146	2489	557	86	60	26
100% Energy - no H2	1792	1068	1617	175	678	25	0	0	0	0	17%	430	305	20,376	1201	104	65	39
100% Energy	1792	1199	1805	128	507	64	92	23	0	0	19%	440	290	4436	1171	90	63	27

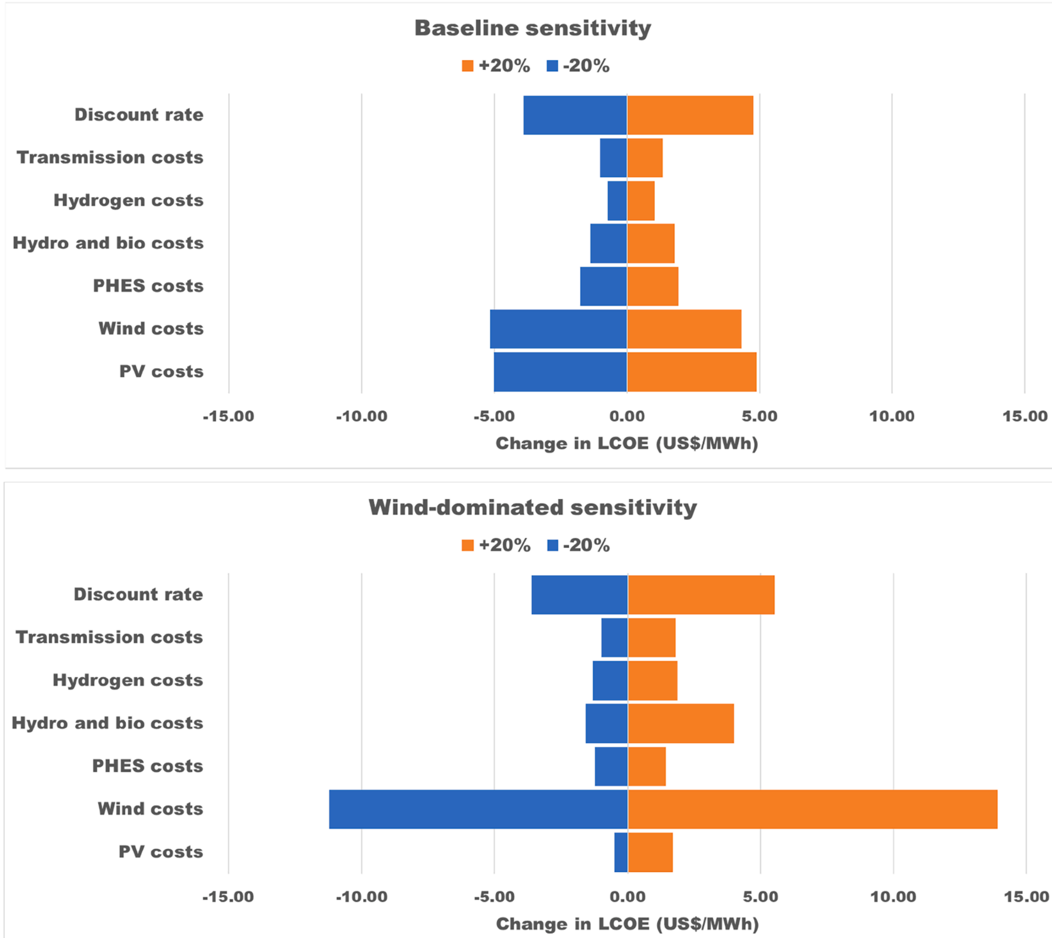

Fig. 12. Sensitivity analysis results for the 'Baseline' scenario (up) and the 'Wind-dominated' scenario (bottom). All cost components are varied ± 20%.

Japan's electricity demand is imported. This would require US$78 billion initial investment and US$784 million of operating and maintenance costs per year. Japan can supply its electricity demand with affordable and reliable renewable energy from domestic resources, perhaps with supplementation from abroad.

If the contribution from solar PV is limited to 20% of total generation to represent the potential shortage of socially-acceptable land for PV deployment, LCOE will increase from US$86/MWh to US$110/MWh, due to the higher cost of offshore wind. However, this is only 8% higher than the current system prices (US$102/MWh) but would effectively eliminate concerns regarding the lack of available land for PV deployment in Japan.

Dispatchable hydrogen has a large beneficial impact on the LCOE, with LCOE increased by US$9/MWh and US$29/MWh in the 'Baseline – no hydrogen' and 'Wind-dominated – no hydrogen' scenarios, respectively. Only a small amount of hydrogen is required to keep the LCOE low (0.3% – 1.5% of total generation). This study assumes that hydrogen is manufactured locally at US$2/kg (US$108/MWh) and then combusted via gas peakers. This assumption can be validated using the modelling results. In the 'Baseline' scenario, annual generation from hydrogen amounts to 4 TWh, which would require 216 million tonnes of hydrogen and approximately 10 TWh of curtailed electricity, assuming 55% efficiency for gas peakers and 45 kWh/kg for electrolyser efficiency [80]. The amount of curtailed electricity required for hydrogen production represents only 6% of the total electricity spillage (160 TWh p.a.).

On the other hand, the modelled hydrogen power is 37 GW, which means that a maximum of 2 million tonnes of hydrogen is required over 1 h to provide 37 TWh of electricity. Assuming that hydrogen storage is built to supply this maximum hydrogen demand for three consecutive hours, which is unlikely to be needed, then the hydrogen storage capacity would be 6 million tonnes. Using IRENA's estimation for future hydrogen system costs (US$200/kW for polymer electrolyte membrane electrolyser plus 3% OPEX, US$1000/kg for hydrogen storage, 25 years lifetime) [80] and assuming 50% annual capacity factor for the electrolyser, the cost of hydrogen (excluding energy costs) would be US $1.9/kg.

In the 'Wind-dominated' scenario, 33% of the total curtailed electricity is required for hydrogen production, at a cost of only US$0.7/kg. The lower cost for the 'Wind-dominated' scenario is because significantly more hydrogen is required per year (4 TWh in the 'Baseline' scenario and 15 TWh in the 'Wind-dominated' scenario), but the required hydrogen power (40 GW compared to 37 GW in the 'Baseline' scenario) is not scaled up accordingly. This means that the cost of hydrogen storage, which has a similar capacity compared to that in the 'Baseline' scenario, is diluted by the higher hydrogen production per annum.

In the short term, hydrogen could also be imported before domestic hydrogen infrastructure is deployed in Japan. For example, Song et al. found that green hydrogen could be produced in China via offshore wind and exported to Japan at a cost below US$2/kg in 2050 [81]. Green hydrogen from Australia may also reach US$1.5/kg by 2030 [82], although shipping cost is not included.

A wide range of scenarios (nuclear, HVDC, Okinawa connection,

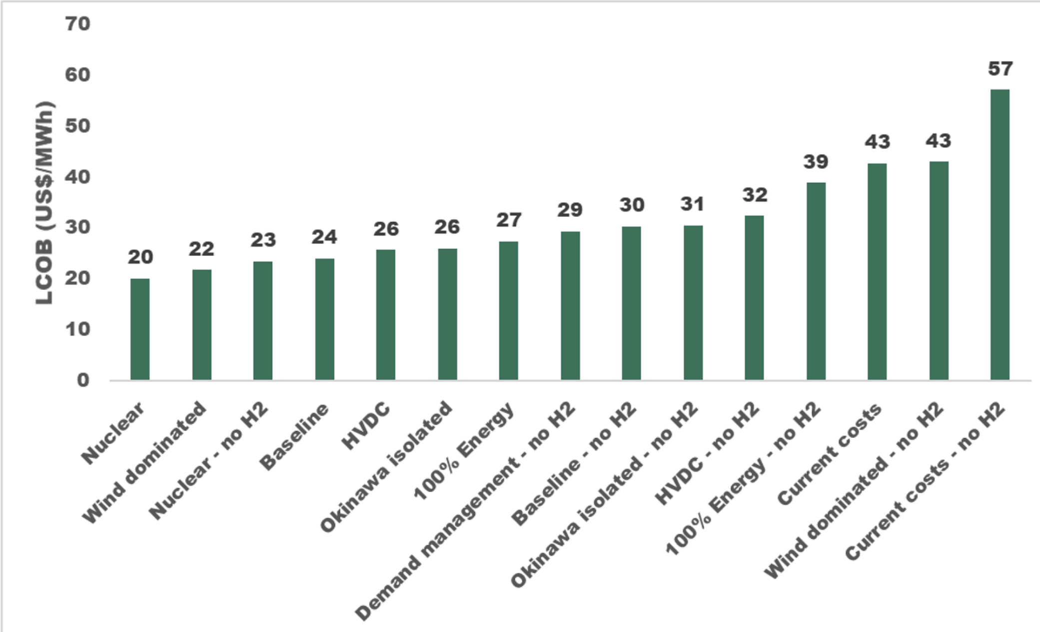

Fig. 13. Cost of balancing 100% renewable electricity.

demand management) result in similar electricity costs. The highest LCOE observed comes from the 'Current costs' scenario. Extreme floating offshore wind costs (US$363/MWh, compared with cost in Europe US$132/MWh [83]) results in almost no wind deployed. Relying on PV only means that all electricity would come from pumped hydro during night, which leads to much higher storage costs. LCOG is also much higher than other scenarios, due to the high current costs of solar PV in Japan (US$132/MWh). Significant cost reduction of solar PV and offshore wind from today's level is needed to enable the cost competitiveness of the proposed renewable system. Cost reductions for solar PV and offshore wind is likely to happen naturally in Japan with more solar PV and offshore wind deployed due to learning curves and increased competition. The authors are positive about significant cost reductions of solar PV and offshore wind in Japan towards global norms over the next couple of decades.

The cost of balancing 100% renewable electricity (LCOB), including costs of storage, transmission, dispatchable hydrogen and spillage, ranges between US$20MWh and US$27/MWh for most scenarios with dispatchable hydrogen available (Fig. 13). The only exception is the 'Current costs' scenario in which the dominance of solar PV means more storage capacity is required to cover the electricity demand during night. Scenarios without hydrogen have higher balancing costs, as it is lower-cost to reserve a moderate amount of hydrogen for continued periods of low solar and wind availability than overbuild additional PHES capacity that is rarely used, as discussed before.

4.3. Decarbonized energy sector

In addition to the electricity sector, decarbonization of other energy sectors are also key steps towards carbon neutrality. Emissions from transport, heat and industry can be effectively eliminated by electrification, which is likely to increase the electricity demand by 30% – 50% [7]. In this study an aggressive electricity demand increase is modelled by doubling the current demand to account for aviation and the chemical industry. The required solar PV, offshore wind and pumped hydro capacities are 26%, 6%, and 8% of the identified potential, respectively, assuming that small amounts of hydrogen are available for balancing variable generation. The overall effect of dispatchable hydro and biomass in meeting energy deficits during critical periods is diminished due to the limitation on further expansion. However, this can be compensated by additional dispatchable hydrogen with a cost penalty of US$4/MWh, and the optimal contribution increases from 0.3% in the 'Baseline' scenario to 1% in the '100% energy' scenario. If hydrogen is excluded, required storage capacity would increase by 180% to ride through occasional cloudy, windless periods, leading to an US$9/MWh increase in LCOE.

Hydrogen is unlikely to compete with solar PV and wind to supply a significant fraction of electricity demand due to its higher costs (US $108/MWh excluding costs for gas peaker). However, it may be competitive as the fuel for shipping, aviation and industrial processes, as direct electrification of these processes is not available at commercial scale yet. Further work will be expanded to sectors that cannot be directly electrified and explore decarbonization options for these sectors.

4.4. Implications for other countries and real-world applications

The modelling results suggest that despite limited land area and high per capita energy consumption in Japan, there are sufficient domestic renewable energy resources in Japan to supply 100% renewable electricity at competitive costs, provided that the costs of solar PV and offshore wind decrease to global norms over the next couple of decades. This study also suggests that there is an important role for solar, offshore wind and off-river pumped hydro in Japan's pathway to decarbonization because these are off-the-shelf technologies that can be deployed right away. The findings of this study provide an important basis for large-scale deployment of solar and offshore wind in Japan, which need to happen soon to meet Japan's 2030 and 2050 targets. The Japanese government need to reconsider the need for large-scale import of hydrogen and clear the path for renewable energy in Japan to allow local developers to learn by doing.

The case study of Japan suggests that the solar-wind-PHES pathway is competitive even in small, developed and densely populated countries. Similar analysis could be carried out for other countries by adopting the methodologies in this study. Germany is already one of the leading countries in terms of renewable energy deployment. With nuclear gradually phased-out and the lack of natural hydro resources, off-river PHES is well-suited to balance variable generation from renewables at low costs in Germany, although systems with larger reservoirs may be required for seasonal storage. Germany has access to very large-scale and high-quality North Sea offshore wind. South Korea has better solar resources compared with Japan and equally good offshore wind resources. It's very likely that the solar-wind-PHES pathway would also work for South Korea, although detailed analysis is needed to understand the renewable energy potential and costs of the 100% renewable energy system.

5. Conclusion

Following many countries' commitment to carbon neutrality, this study investigates whether supplying 100% renewable electricity in small, developed and densely populated countries like Japan with domestic renewable energy resources is a feasible and affordable option. A GIS-based renewable energy resource assessment is performed, and a 40-year hourly energy balance analysis is presented. The hypothetical electricity system is largely supplied by solar PV and offshore wind, with intermittent generation balanced by existing hydro and biomass, dispatchable hydrogen, pumped hydro energy storage and transmission. It is found that Japan has sufficient solar PV, wind, and pumped hydro potential to support 100% renewable electricity and even 100% renewable energy. Importantly, a wide range of scenarios yield costs in the range US$86–110/MWh which are competitive with current spot prices. Cost of balancing 100% renewable electricity in Japan ranges between US$20–27/MWh for most scenarios with hydrogen. The findings of this study give confidence that 100% renewable electricity via solar PV, wind, and pumped hydro in Japan is workable despite uncertainties in constraints and costs. This offers an important alternative pathway to decarbonization in Japan in addition to those presented in the METI meeting [8]. It also suggests that there are important roles for solar PV, wind, and off-river PHES even in small, developed and densely populated countries. The methodologies of this study can be readily applied to other similar countries, such as Germany and South Korea.

CRediT authorship contribution statement

Cheng Cheng: Methodology, Software, Formal analysis, Data curation, Writing – original draft. **Andrew Blakers:** Conceptualization, Writing – review & editing, Supervision. **Matthew Stocks:** Validation, Writing – review & editing, Supervision. **Bin Lu:** Investigation, Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enconman.2022.115299.

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