Japan's Transition to 100% Clean Energy: Opportunities and Challenges

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Abstract. Japan faces significant energy challenges due to its heavy reliance on imported fossil fuels, which has led to high greenhouse gas emissions, elevated energy costs, and concerns about energy security. This study assesses the feasibility of transitioning Japan to a 100% clean energy system, with a focus on evaluating the technical potential of its dominant renewable resources. By analyzing current energy data and employing sector-specific modeling, this article estimates the generation capacity of solar PV, onshore and offshore wind, hydro, geothermal, and nuclear power. Findings indicate that these sources can collectively meet over 90% of Japan's projected end-use energy demand following efficiency gains. Solar rooftop PV and offshore wind are identified as the key solution in these transitions, but the realization of this potential is constrained by high upfront costs, grid integration challenges, geographical limitations, and socio-political barriers, particularly regarding nuclear energy. This paper concludes that while a predominantly renewable-powered Japan is technically attainable, it requires strategic infrastructure investment, policy support, and international cooperation to overcome these hurdles. The insights offered may also serve as a valuable reference for other resource-constrained island nations.

Keywords: Japan, Energy Transition, Clean Energy, Energy Security, Solar potential.

1 Introduction

Two of the most pressing global issues today are climate change and environmental pollution. Increased reliance on fossil fuel energy has been the primary driver of ecological degradation and severe public health issues. In the case of Japan, its energy structure has been heavily dependent on imported fossil fuels, especially after the Fukushima nuclear accident in 2011 led to a reduction in nuclear power output [1]. As a result, greenhouse gas emissions have remained high, and the country faces growing challenges in balancing environmental protection and financial considerations. Meanwhile, Japan's prolonged history of lacking fossil fuel is making the country especially eager to transform its energy sector and to ensure its energy security. In the proposed future plan of switching to 100% clean energy, solar and wind energy usually account for the major part of supply. However, Japan has vast urban areas, a dense population,

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and limited access to spare territory, which by some means blocks the wide promotion of onshore wind, hydroelectric, and solar panels. Alternatively, Japan is the eighth-largest ocean owner and, by its adjacent location to the Circum-Pacific Seismic Belt, owns significant geothermal energy reserves. In fact, it is supported by some scholars that Japan is actively seeking to make a restart of its nuclear energy after the Fukushima disaster, while this contradicts the current consensus in Europe [2]. This study explores the clean energy solution unique to Japan, which can possibly be applied to other similar countries, which is done by proposing a 100% WWS energy replacement plan and contrasting it to current situations. Based on historic research and open data, this study aims to identify the major challenges and opportunities involved and provide insights that may also be applicable to other island nations or resource-constrained economies by finding out the viability of a thorough national transition.

2 Current Situation

2.1 Current Energy Consumption & Generation Status

According to IEA 2022 data, the annual total energy supply of end-use energy in Japan is 16 395 446 TJ, while only 2 068 371 TJ comes from domestic generation. For all the rest, 14327075 TJ that comes from fossil fuel, Japan has to rely on importing. In fact, Japan imported 15 487 229 TJ of biofuels and fossil fuel. This heavy dependence not only results in high energy costs due to volatile global fuel prices and transportation expenses but also undermines energy security, as supply stability is constantly threatened by global crises and market disruptions [3]. Before the Fukushima nuclear accident, Japan had chosen nuclear energy as its primary source of clean energy, generating 30% of its energy mix, but now this number has to recover from just 3% [4]. There lie both challenge and opportunity: while Japan has to face a temporary energy shock, it forces Japan to reconsider the role of nuclear energy and to elevate the importance of mainstream sources of clean energy like wind and solar. Currently, despite limited territory, Japan has made it to generate 23% of its electricity with renewable energy, far higher than the global average (Table 1).

Table 1. The 7th Strategic Energy Plan by Agency of Natural Resources and Energy of Japan, Feb 2025

		Fiscal Year 2023	Fiscal Year 2040
Energy self-sufficiency rate		15.2%	30%-40%
Electricity generated		985.4 billion kWh	1.1 to 1.2 trillion kWh
Power generation mix	**Renewable energy**	22.9%	40%-50%
	Solar PV	9.8%	23%-29%
	Wind power	1.1%	4%-8%
	Hydropower	7.6%	8%-10%
	Geothermal power	0.3%	1%-2%

		Fiscal Year 2023	Fiscal Year 2040
	Biomass	4.1%	5%-6%
	Nuclear power	8.5%	20%
	Thermal power	68.6%	30%-40%
Final energy consumption		300 million kL	260 to 270 million kL
GHG reduction rate		22.9%	73%

2.2 Reasons for Choosing Clean Energy

Besides mitigating the greenhouse effect and global pollution, the transition to WWS energy offers multiple co-benefits.

First, renewable technologies are becoming increasingly cost-competitive and, in many cases, already provide electricity at a lower levelized cost than fossil fuels. After the Fukushima nuclear accident, the lower cost of coal once attracted the Japanese government to this pollutive energy, but according to official reports, the estimated energy cost of clean energy has been significantly lower than LNG, the current transitional energy source [5]. Another economic reason to choose it is the reduced medical insurance burden as a result of fewer pollutant particles.

Second, compared with the capital-intensive fossil fuel industry, renewable energy deployment is more labor-intensive, which means it has greater potential to stimulate local employment and economic revitalization.

Finally, considering the high efficiency at which electric devices run, the transition to WWS energy will significantly reduce the total end-use energy, so both the societal cost and the pressure on the grid will be reduced. Current total end-use energy consumption in Japan is estimated to be 10,789,067 TJ per year. If all equipment used in each sector is replaced by efficient devices, roughly 30% of end-use energy could be saved (see table 2), so this study will only need to meet a total end-use demand of 6,560,445 TJ (1822 TWh). Now, Japan is already on the way to replacing old electrical appliances, and hydrogen-fueled cars are becoming a popular trend among car producers, both accomplishing this goal [6].

Table 2. Estimated end-use energy upon transitioning to new equipment

Sector	Consumption (TJ)	Efficiency Factor	Upon Conversion (TJ)
Industry	3,165,434	0.80	2,532,347
Transport	2,669,288	0.60	1,601,573
Residential	1,722,977	0.65	1,119,935
Commercial and Public Services	1,866,557	0.70	1,306,590
Total	9,424,256	—	6,560,445

3 Plan for Each of the Energy Sectors

3.1 Solar PV

The biggest challenge Japan faces is its limited territory, which means there won't be enough space for large solar panel farms. Japan has now deployed solar PV that is able to produce a power of 84.9 GW, mainly composed of rooftop PV. Japan will still stick to rooftop PV, considering its two priorities: First, rooftop systems can be adopted voluntarily by individual households, and widespread public adoption is already underway as part of the effort to meet clean energy targets [7]. Second, because of their decentralized nature, rooftop PV installations can supply electricity locally without relying fully on the national grid, thus reducing grid stress and improving overall efficiency. Meanwhile, Japan is also seeking to build trial offshore floating solar farms [8]. These floating PV farms are economically less attractive, but they might be a necessary compromise with land scarcity and rising energy demand. This will lead us to the primary concern: is the Japanese rooftop area really sufficient?

One team from Osaka City University has finished one thorough estimation of the rooftop PV potential in Osaka. According to GIS data, the accessible rooftop area in Osaka is roughly 42 km^2, and upon considering all factors, each square meter deployed with solar panels will receive solar energy equal to 1407 kWh per year. At the transition coefficient of 24%, it will provide 53200 TJ each year [9]. According to population and city coverage rate estimation, the total available rooftop area in Japan is roughly around 2000 km^2. Assuming similar parameters can be applied to all rest areas (given the relatively uniform conditions across Japan for PV deployment), this will be at maximum able to generate 2,533,333 TJ (704 TWh) of electricity each year.

Now look at the economic balances. For each kW of nameplate capacity, it costs 184,500 Japanese yen in one-time capital expenditure and an annual operation and maintenance cost of 3400 yen. For the whole of Japan, another 215 GW of nameplate capacity is required, so there will be a total of 40.0675 trillion Japanese yen in one-time capital expenditure and 731 billion Japanese yen in annual operation and maintenance cost per year. Currently, the cost of rooftop PV is below 12 yen per kWh, and the domestic average is 16 yen per kWh, so this will annually save 2.8 trillion yen. Excluding the maintenance cost, it will take no more than 20 years to get all the expenditures.

3.2 Onshore & Offshore Wind Energy

Onshore Wind With limited land size, Japan does not tend to rely as heavily on onshore wind as other countries. While the total power potential of Japanese onshore wind energy is 310 GW, excluding the resistance from tourism, noise pollution, and grid pressure, the actual accessible power will be just around 65 GW. Take the CF as 25%; the annual energy generated will be 512,460 TJ. Still, Japan is far from realizing this goal, as only 5.8 GW of wind turbines have been deployed. Plus, another contradiction will be that while Hokkaido hosts most of Japan's premium wind resources, the remote area's grid infrastructure is too weak to support large-scale electricity transmission, making grid reinforcement indispensable.

Offshore Wind Currently, Japan has deployed onshore and offshore wind power systems with a nameplate capacity equal to 6 GW, but only 0.3 GW comes from offshore turbines. This is caused by the fact that most offshore turbines are installed at ports, and it was not until the recent revision of ocean development laws that the broad marine EEZ area was taken into consideration. Utilizing all possible marine areas, a potential of 1676 GW is available, while the best-adapted areas will provide 94 GW for the fixed-bottom type and 519 GW for the floating type. Still, as EEZ also plays an important role in transportation and fishery, it won't totally make way for electricity generation. Assume 0.5% of the EEZ area (22,350 km^2) is deployed with turbines (the turbine is set to be the current medium-size turbine, Vestas V117); the annual energy supply will be 440 TWh (1,585,867 TJ). In this case, a sum of 111 GW of nameplate capacity will be deployed. But this plan could also face some challenges, mainly for its high cost. Despite the high economic effect in some specific areas, globally offshore wind farms have to rely on government incentives to remain viable, and the energy cost could be two or three times that of onshore wind, even exceeding traditional fossil fuel. Over the years of 2010-2020, this number has decreased by 48%, so hopefully large-scale utilization could be achievable in the future [10]. One extra solution to this will be the large-scale installation of an ocean grid system, which is expected to lower the overall construction cost by 20%.

3.3 Hydro Energy

Japan is a small country with a relatively flat landscape, so it has limited access to hydroelectric energy. Most of Japan's hydroelectric potential has been developed, and the rest are mainly those economically or politically unsuitable for exploitation. Currently, Japan can rely on hydroelectric to produce 277279 TJ (77 TWh) of energy per year [11]. The current average CF is calculated to be about 18%, so if Japan exploits 30% of the rest of the potential and sets CF to be 15%, it will provide an extra amount of 7.5 TWh per year. Conclusively, Japan will use hydroelectric energy to meet 84.5 TWh of electricity demand.

Interestingly, hydroelectricity, as a type of stable energy source, in Japan exhibits a low level of CF. This is caused by the fact that the majority (nameplate capacity 27 GW) of it is used for pumped storage rather than continuous generation. These plants operate mainly during peak demand or to balance variable renewables, so they run only part of the time, lowering the average utilization rate. Looking at continuous power generation, the CF will be as high as 0.34. Granted, this is unavoidable, as keeping the grid stable has always been a crucial problem in the development of WWS energy. Moreover, Japan's rivers are mostly short and fast-flowing, which limits the scale of new dam construction and reduces the feasibility of large reservoir-type projects. This means future development will mostly rely on small-scale distributed facilities or upgrading existing plants, and hardly any new premium hydroelectric plants can be developed.

3.4 Geothermal Energy

Japan is a country of rich geothermal energy, considering its adjacency to the Pacific Rim of Fire. Despite some already put-into-use factories, further exploitation doesn't seem to go smoothly. This is because most of its geothermal sources occur in national parks or tourism destinations famous for springs, where heavy industrial exploitation isn't welcomed [12]. Meanwhile, the current major way of utilizing geothermal energy is quite traditional: bathing or the spring itself is a highly efficient way of direct use (see table 3). Because the power density as well as land use of geothermal energy vary greatly by region, and geothermal energy in total is just a minor part of WWS, let's just assume the installed nameplate capacity of geothermal energy to double. Current installed nameplate capacity (electricity plus heat pump) is around 2887 MW, so at the CF of 37.9%, the doubled amount will generate 20 TWh each year.

Table 3. Statistics of Japanese geothermal energy in 2020

Use	Installed Capacity (MWt)	Annual Energy Use (TJ)	Capacity Factor
Individual Space Heating	91.97	2467.32	85.0%
District Heating	111.37	1669.51	47.5%
Greenhouse Heating	24.71	267.19	34.3%
Fish Farming	7.61	123.10	51.3%
Animal Farming	0.36	3.41	30.0%
Agricultural Drying	6.02	76.73	40.4%
Industrial Process Heat	1.06	27.02	80.8%
Snow Melting	150.17	431.98	9.1%
Bathing and Swimming	1999.42	24591.00	39.0%
Other uses	14.69	301.11	65.0%
Subtotal	2407.38	29958.37	39.4%
Heat Pumps	163.44	764.90	14.8%
Total	2570.82	30723.27	37.9%

3.5 Nuclear Energy

Since the 2011 Fukushima disaster, the Japanese government has always held contradictory attitudes towards nuclear energy. Before, it had planned to rely on nuclear energy to generate 30% of its total energy consumption, but now this number varies around 20%, depending on which party is in power. In 2022, Japan's nuclear factories can generate 170 TWh of energy per year. In recent years, this number is developing or restoring quickly because many closed reactors have undergone a restart: of the 33 reactors Japan currently owns, while only 14 are currently at work, 3 are ready for restart and another 8 are applying for permission. These 11 power plants will provide a nameplate capacity of 12 GW, almost doubling the capacity. If the overall CF can be restored to the 2010 level (288 TWh), together with newly built nuclear power plants, it isn't too far from the 300 TWh goal. Still, there will be a long way to go, as the restoration of nuclear plants is quite hard. With aging infrastructure and increasingly strict safety regulations, the process of restarting reactors often takes far longer than expected. Even the plants already permitted to restart are not guaranteed to resume operation. Plus, the Fukushima accident is still contributing to widespread discussion and doubt about whether nuclear development should still be permitted [13].

4 Conclusion

As demonstrated above, mainstream sources of clean energy are sufficient to support over 90% of Japan's total energy demand. For such a small country with advanced industry and dense population, this blueprint is truly remarkable. It would not only help achieve a greener future but also greatly enhance Japan's energy security by substantially reducing its reliance on energy imports. However, as a highly idealized blue sketch, it will also face multiple challenges. Because it relies heavily on decentralized rooftop PV and offshore wind, the foundation of this plan is somewhat fragile, and high upfront investment together with long payback periods may discourage investment and slow down large-scale deployment. Japan's geography, with limited flat land, frequent natural disasters, and fragmented grid systems, adds further complexity to renewable expansion. Investing in energy storage, grid modernization, and regional interconnection will be essential to stabilize supply.

Moreover, public response is likely to pose challenges. Long payback periods and exploitation of cultural assets will both arouse public resistance. The viability of the nuclear plan is also doubtful, as the government is not fully sure about the revitalization of nuclear power, especially when Europe and quite a few other countries are abandoning it. To maximize the economic efficiency, the first thing Japan needs to do will be to update its infrastructure and equipment, from grid construction to electric devices. Besides fitting with clean energy generations, it by itself is a part of reducing end-use energy demand by improving working efficiency.

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