Potential for rooftop photovoltaics in Tokyo to replace nuclear capacity

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Abstract

In 2010, nuclear power accounted for 27% of electricity production in Japan. The March 2011 disaster at the Fukushima Daiichi power station resulted in the closure of all of Japan’s nuclear power plants and it remains an open question as to how many will reopen. Even before the loss of nuclear capacity, there were efforts in Japan to foster the use of renewable energy, including large scale solar power. Nuclear power plants in Japan provided more than just base-load by storing energy in large scale pumped hydroelectric storage systems, which was then released to provide some peaking capacity. If this storage were instead coupled to current generation rooftop solar systems in Tokyo, the combined system could help to meet peak requirements while at the same time providing ~26.5% of the electricity Tokyo used to get from nuclear output, and do so 91% of the time. Data from a study of rooftop space and a 34 yr data set of average daily irradiance in the Tokyo metropolitan area were used. Using pumped hydroelectric storage with 5.6 times this rooftop area could completely provide for TEPCO’s nuclear capacity.

Keywords: photovoltaic, nuclear power, pumped hydrostorage, renewable, Japan, Tokyo, Fukushima, TEPCO

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1. Introduction

In March of 2011 a massive earthquake and tsunami struck Japan, crippling four of the six nuclear reactors at the Fukushima Daiichi nuclear power facility and causing the release of radioactive material into the biosphere [1–4]. Within a year, all of Japan’s 54 nuclear reactors had been shut down [5, 6], electricity costs rose by as much as 18% [6], and public opposition to nuclear energy increased drastically to 74% [6]. Utilities responded to the loss of nuclear power by increasing their importation of fossil fuels to generate more output from conventional power plants [6].

Japan has few indigenous resources for producing power [6]. In 2010, Japan imported 4.3 million bbl d\(^{-1}\) of oil, of which 178,000 bbl d\(^{-1}\) of crude oil were used for electricity production, as well as 207 million short tons of coal and 3.4 Tcf of natural gas, both of which are used predominantly for electricity production [7]. Together these resources provided 63% of Japan’s electricity with 27% coming from nuclear power and 10% from renewable sources (largely hydro power) [7]. The energy mix of some utilities favored nuclear power to an even higher degree. The Tokyo Electric Power Company, TEPCO, provided as much as 40% of the electricity for the greater Tokyo area using nuclear energy alone [8]. However, the Fukushima accident resulted in widespread calls for the replacement of nuclear power with other energy sources [6]. One option to do this would be with traditional thermal plants; a recent study estimated that it would require Japan to double its current capacity of either...
Table 1. Japan’s photovoltaic policies. The different policies implemented to help encourage photovoltaic installations in Japan, including when they were in effect and a basic description of each policy. Data from [17].

| Title                                      | Start  | End    | Type          | Funding                        | Description                                                                                                                                 |
|--------------------------------------------|--------|--------|---------------|--------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------|
| Subsidy program for residential PV system  | 1994   | Mar-06 | Subsidies     | (Shown in table 2)           | Subsidy provided to individuals as well as owners and developers of housing complexes. Covers cost of the PV module, the peripheral equipment, distribution lines, and installation labor. |
| Promotion for development and dissemination of PV systems | 1997   | Superseded | RD&D         | 1999: 28.49 BYen, 2000: 28.8 BYen, 2001: 32.2 BYen, 2002: 35.9 BYen | (1) Tech development to accelerate PV system dissemination. (2) Demonstration: PV field test program for industrial applications. (3) Introduction and promotion to residences. |
| Introduction of solar power in Government office buildings | 2001   | Superseded by non PV emission policy | PV acquisition   | 860 MYen in 2001 | Japanese government introduced 410 kW of solar power in 13 offices. Encouraging other institutions to introduce solar power. |
| Subsidy for residential PV systems         | 2009   | In force | Subsidies     | (Shown in table 2)           | Subsidy of 70 kYen kW$^{-1}$ for systems of installation cost of 650 kYen kW$^{-1}$ or less and a max capacity of 10 kW. Also, system must have proper qualifications, efficiency, and warranty. |
| New purchase system for solar power generated electricity | 2009   | 2019   | Incentives    | Through surcharge collected by electric utilities | Starting 1 Nov 2009, electric utilities are required to purchase excess power produced by PV. From households: 48 Yen kWh$^{-1}$, from non-households: 24 Yen kWh$^{-1}$. |

coal or natural gas plants, with estimated costs to exceed $84 billion, adjusted to 2006 USD [9].

Another option would be to dramatically increase the use of renewable energy in Japan [10]. Japan has historically focused much of its renewable energy efforts on the development of solar photovoltaics, figure 1 [11], and it currently has the third largest installed capacity in the world as a result [12]. Photovoltaics are well established in Japan and have been promoted through a variety of programs since the mid-1970s, tables 1–2, in part because of their export potential [13]. The development of large scale photovoltaic systems was already underway in Japan before the events at Fukushima as part of the PV2030 initiative [13–16]. As a result, any effort to replace or reduce the role of nuclear power via renewable energy systems would likely feature large-scale photovoltaics.

The potential for solar energy to contribute to electricity production is well understood [16, 31–33], especially in locations with high afternoon energy demand [34]. Its use as a replacement for nuclear power, a base-load energy source [35], is less established but has also received considerable attention [36, 37]. A critical factor here is the ability to smooth diurnal and weather based variations, which could be done using large-scale storage capacity [31, 38–41].
Table 2. Subsidy amounts given to consumers based on the installed capacity of a system, adjusted to 2010 USD. The budget indicates the total amount of money allotted for these subsidies in a particular year. While the subsidy program expired in 2005, it was reestablished in 2009 and extended in the fall of 2011, following the Fukushima disaster [14, 25]. MUSD = million US dollars. All dollar amounts were converted from Japanese Yen using the average exchange rate of each year [29], and then adjusted for inflation to 2010 USD [30].

| Year | Subsidy amount (2010 USD W$^{-1}$) | Budget (2010 MUSD) | Reference |
|------|-----------------------------------|-------------------|-----------|
| 1994 | 14.39$^{a}$                      | 28.79             | [18]      |
| 1995 | 10.88$^{a}$                      | 50.20             | [18]      |
| 1996 | 7.48$^{a}$                       | 52.40             | [18]      |
| 1997 | 3.86$^{a}$                       | 124.68            | [17, 18]  |
| 1998 | 3.48$^{b}$                       | 144.26            | [17, 18]  |
| 1999 | 3.68$^{b}$                       | 188.66            | [17, 18]  |
| 2000 | 3.17$^{c}$                       | 170.38            | [19]      |
| 2001 | 1.23$^{d}$                       | 238.22            | [20]      |
| 2002 | 0.97$^{d}$                       | 224.66            | [21]      |
| 2003 | 0.92$^{d}$                       | 107.32            | [22]      |
| 2004 | 0.48$^{d}$                       | 56.55             | [23]      |
| 2005 | 0.20$^{d}$                       | 26.36             | [24]      |
| 2006 | 0.0$^{e}$                        | 0                 | [14, 25]  |
| 2007 | 0.0$^{e}$                        | 0                 | [14, 25]  |
| 2008 | 0.0$^{e}$                        | 0                 | [14, 25]  |
| 2009 | 0.76$^{e}$                       | 456.80            | [17, 26]  |
| 2010 | 0.80$^{f}$                       | 622.70            | [17, 27]  |
| 2011 | 0.58$^{g}$                       | 424.31            | [17, 28]  |

$^{a}$ Subsidy amount up to 50% system price.
$^{b}$ Subsidy amount up to 1/3 system price.
$^{c}$ Subsidy amount: $3.17$ W$^{-1}$ for system size up to 10 kW systems in first half of year, $2.12$ W$^{-1}$ for system size up to 4 kW in second half.
$^{d}$ System size up to 9.99 kW.
$^{e}$ Initial budget 217.8 MUSD, supplemented with 239 MUSD. System size must be less than 10 kW with a cost not to exceed $7.60$ W$^{-1}$.
$^{f}$ Initial budget 457.2 MUSD, supplemented with 165.5 MUSD. System size must be less than 10 kW with a cost not to exceed $7.40$ W$^{-1}$.
$^{g}$ System size must be less than 10 kW with a cost not to exceed $7.30$ W$^{-1}$.

In this regard, Japan is in the unique position of already possessing the largest capacity of pumped hydroelectric storage in the world, a total of 24.6 GW [42] and it has been used largely as a way of storing excess nuclear power for use during peak demand. TEPCO itself owns 7.28 GW [43].

Pumped hydroelectric storage is a large-scale storage medium with a high round-trip efficiency, 65–85% [38, 39, 44], and is well suited for use with intermittent renewable sources such as solar power [39]. This storage medium can have capacities of 100s to 1000s MW, with storage times up to months (or even years) [39] and is capable of discharging energy on hourly or daily time scales [38, 39]. Such long-term, large-scale storage capability allows for daily and even seasonal variations to be accounted for via storage, helping to reduce the effects of variability in surface solar irradiation. Recent work has shown that solar power is capable of providing a reliable stream of electricity when an appropriately sized array and storage facility are coupled [45].

Figure 2. Yearly average solar irradiance of Japan. Data are based on a three-year average of satellite data from the DX data set of the International Satellite Cloud Climatology Project [47]. This shows the variation in surface solar irradiation across the country.

Figure 3. Surface solar irradiance for Tokyo prefecture. These irradiance values are averaged over a 24 h period. This shows the changes in surface irradiance that might be expected in Tokyo. These data are from 1996, from a ground-based location in Tateno, Japan [48].

A potential issue with solar power systems is the availability of sufficient land, and there has been opposition to the development of large-scale photovoltaics in some countries [46]. Studies assessing the potential impact of using roof area for photovoltaic systems are often done using satellite data and simple models for the fraction of roof area that receives sufficient sunlight for solar panel installation [47, 48]. As with other urban regions rooftop area is a largely untapped solar resource in the greater Tokyo area. Data from both satellite and ground-based measurements indicate that Japan receives a yearly average irradiance of 125–162 W m$^{-2}$ [49–51], figure 2. The greater Tokyo region of Kanto has $\sim30\%$ of Japan’s population and a yearly average irradiance of 151 W m$^{-2}$ [50]. A single year can be seen in figure 3, and the historical average year in figure 4. Solar power is particularly suited for Japan, as the modularity of these units make them capable of withstanding earthquakes and tsunamis compared to nuclear plants [51].

Here we present an analysis of how rooftop photovoltaics in the greater Tokyo region may be used to replace or supplement the area’s nuclear capacity. If available pumped hydroelectric storage were coupled to current generation rooftop solar systems in greater Tokyo, the combined system...
Figure 4. Variation in surface irradiance in Kanto. The graph shows the average surface irradiance in Kanto for each day of the year, as well as the actual data that contributed to the average. Each data point corresponds to the 24 h average irradiances for an individual day and are taken from a 34 yr data set that is available for Tateno [48].

Figure 5. System schematic. Diagram of combined solar photovoltaic and pumped hydroelectric storage. Energy is sent to the grid either directly from the array or from the storage facility. This could help meet peak requirements while also providing power equivalent to ~26.5% of Tokyo’s nuclear capacity. Importantly, the system would be able to do this 91% of the time, which is equivalent to the capacity factor of the US nuclear fleet in 2010 [52]. We use a 34 yr data set of ground-based solar irradiance data for the region along with data on the available of rooftop area to assess the system performance.

2. Methods

As with other countries, Japan has used feed-in tariffs to promote the development of residential and commercial photovoltaic systems [13]. We assume that rooftop photovoltaics in the Kanto region feed into the grid and that production in excess of daily consumption is diverted to pumped hydroelectric storage, or into other regions if this is at capacity, figure 5. Data on surface solar irradiances for the Kanto region were taken from ground-based global solar irradiance measurements in Tateno, a city near Tokyo, that are available through the World Radiation Data Center. These data provide a 34 yr history of 24 h average irradiances [50] e.g. figure 3. Rooftop areas for the Kanto region were adapted from recent studies of the metro Tokyo region [53, 54]. We assume current generation photovoltaics with a median efficiency of 14.5% [55], the efficiency of the entire system was assumed to be 13%, table 3.

Table 3. Solar system components. Parameters used for the efficiencies of the system. The total efficiency of the solar panel system was calculated by multiplying the module, inverter, and transmission efficiencies, 12.9%.

| Parameter                          | Value | Reference |
|------------------------------------|-------|-----------|
| Module efficiency (%)              | 14.5  | [54]      |
| Round-trip storage efficiency (%)  | 78    | [42]      |
| System efficiency                  |       |           |
| Inverter (%)                       | 94    | [55]      |
| Transmission (%)                   | 95    | [42]      |

2.1. Energy flow model

The total output of the rooftop arrays can be written:

\[ E_i = \eta \int_{24 \text{ h}} I(t)A_{\text{array}} \, dt. \]  

(1)

Here \( E_i \) (J) is the energy produced, \( \eta \) is the efficiency of the solar panels, \( I(t) \) (W) is the surface solar irradiation at time \( t \), \( A_{\text{array}} \) (m\(^2\)) is the total area of the arrays. The integral in equation (1) is over a 24 h period for each day and is taken from the 24 h average irradiance data for Kanto given in [50]. The energy produced by the arrays is partitioned into three components:

\[ E_j = E_K + E_s + E_e \]  

(2)

where \( E_K \) (J) is the energy sent directly to Kanto to help meet its base-load electricity needs, \( E_s \) (J) is the energy directed into pumped hydroelectric storage, and \( E_e \) (J) is the excess energy produced by the array that cannot be used within Kanto or stored (it is assumed to go to the grid). If we let \( E_b \) equal the 24 h base-load energy requirement for Kanto, as determined from a TEPCO load curve (supplemental information available at stacks.iop.org/ERL/8/014042/mmedia), and \( f \) be the fraction of this to be met using the distributed PV system, then:

\[ E_K = \begin{cases} E_b & E_i \geq fE_b \\ E_i & E_i < fE_b \end{cases} \]  

(3)

\[ E_s = E_i - fE_b \quad E_i \geq fE_b, \text{ storage not full} \]  

(4)

\[ E_e = E_i - fE_b \quad E_i \geq fE_b, \text{ storage full} \]  

(5)

When \( E_i < fE_b \), energy is removed from the storage by the amount \( fE_b - E_i \), until storage is depleted, and sent to Kanto.
The amount of energy in the storage facilities is noted at the end of each simulated day, as are $E_g$, $E_s$, and $E_c$ for each day. We define the solar system’s capacity factor to be the fraction of the desired continuous power output that can be met over the course of a year:

$$CF = \frac{\sum_{\text{year}} (E_K + E_s)}{\sum_{\text{year}} (E_b)}.$$  \hspace{1cm} (6)

2.2. Rooftop area

Izumi and Matsuyama performed an analysis of the area available for rooftop greening in Tokyo City using a satellite analysis [53, 54]. They determined the total rooftop space suitable for gardening, flat and free of obstruction, to be 50.69 km$^2$ [54] and we assume that this would also be appropriate for photovoltaic panels. While non-residential roofs in the study area were determined to be generally flat, 41.9% of low- and middle-rise residential roofs were found to be sloped [53]. While the actual pitch, orientation and free area of these roofs was not assessed, previous studies in other urban areas have estimated the fraction of sloped roof area that would be suitable photovoltaic panels [46]:

$$A_{\text{sloped}} = 0.28 \times A_{\text{roof}} / \cos(20^\circ).$$  \hspace{1cm} (7)

Here $A_{\text{sloped}}$ (W) is the estimated sloped roof area available for solar panel, $A_{\text{roof}}$ (W) is the floor plan area of the roof, $\cos(20^\circ)$ accounts for the sloping of the roof, and 0.28 is a corrective coefficient [46]. Izumi and Matsuyma report $A_{\text{roof}}$ from to be 33.7 km$^2$ [53, 56], and equation (7) then gives $A_{\text{sloped}} = 10.03$ km$^2$ for Tokyo City.

To estimate the available roof area in the Kanto region, we assumed that the usable rooftop space scales linearly based on number of buildings of a given type, and that the number of buildings scales with the population density:

$$A_{\text{TP}} = \frac{A_{R \text{- } \text{TC}}}{B_{R \text{- } \text{TC}}} N_{R \text{- } \text{TP}} + \frac{A_{NR \text{- } \text{TC}}}{B_{NR \text{- } \text{TC}}} N_{NR \text{- } \text{TP}}.$$  \hspace{1cm} (8)

Here $A_{\text{TP}}$ is the total rooftop area available for photovoltaics in Tokyo Prefecture, $A_{R \text{- } \text{TC}}$ and $A_{NR \text{- } \text{TC}}$ are the roof area from residential and non-residential buildings in Tokyo City, table 4 [53], $B_{R \text{- } \text{TC}}$ and $B_{NR \text{- } \text{TC}}$ are the number of residential and non-residential buildings in Tokyo City [53], and $N_{R \text{- } \text{TP}}$ and $N_{NR \text{- } \text{TP}}$ are the number of residential and non-residential buildings in Tokyo Prefecture [56]. Japanese 2010 census data were used for $N_{R \text{- } \text{TP}}$ and $N_{NR \text{- } \text{TP}}$ and equation (8) yielded an available area for Tokyo Prefecture of 93.4 km$^2$.

Tokyo is only one of the nine prefectures in the Kanto region, serviced by TEPCO, figure 6 [57]. Census data on the number of buildings in these regions is not available. For these areas we assume that the number of buildings per capita scales linearly for regions of similar population density [58, 59]. The average number of buildings per person in the Tokyo Prefecture were determined using 2010 census data [60]. These ratios, defined as $BP_{\text{res}}$ and $BP_{\text{nonres}}$, were 0.22 residential buildings per person and 0.019 non-residential buildings per person, respectively. The total rooftop area in Kanto is then given by:

$$A_{\text{total}} = P \left( BP_{\text{res}} \frac{A_{R \text{- } \text{TC}}}{B_{R \text{- } \text{TC}}} + BP_{\text{nonres}} \frac{A_{NR \text{- } \text{TC}}}{B_{NR \text{- } \text{TC}}} \right) + A_{\text{TP}}$$  \hspace{1cm} (9)

where $P$ is the population of Kanto, excluding Tokyo Prefecture. A summary of the rooftop area available throughout TEPCO’s service area can be found in table 5.

3. Results and discussion

A major issue with solar power is its ability to provide a consistent stream of energy in a reliable manner. Variability
caused by weather and day/night cycling can be diminished through the use of storage systems. The total energy that can be produced by a solar array is ultimately set by its area, its efficiency, and the surface irradiances. Using available data and equations (7)–(9) we estimated the suitable rooftop area in Kanto to be 297.5 km$^2$. Such an array would have an installed capacity of 43.1 GWp. The pumped hydroelectric storage available for this region through TEPCO is reported to be 7.28 GW, table 6. Daily average surface solar irradiances were compiled from the 34 yr database [50]. The collective data on array area, storage and surface irradiance were used to determine the level of base-load power that could be provided by the distributed photovoltaic system, as well as the overall amount of energy that could be expected per year.

Figure 7 shows the expected energy produced from the array, supplied to the grid, and in storage over the course of a year when $E_K = P_b = 4.8$ GWe. The excess energy is also shown. This power output can be met by the photovoltaic system when coupled to 7.26 GWe of pumped hydro storage.

Figure 8(a) shows the fraction of time when this level of base-load capacity would not be met between 1972 and 1996, broken down by month. Importantly, the system is able to always provide at least 63% of the required load in each month. Figure 8(b) shows the number of consecutive days that lack full power during this time period. As can be seen, Tokyo would typically be unable to meet the desired base-load output for fewer than 5 days in a row using the photovoltaic arrays. Ten or more sequential days during which the system could not meet the base-load output desired occurred 30 times during this 25 yr period. However, these periods are clustered during the winter, and regular maintenance could be scheduled to take advantage of this periodicity. This coupled system would produce an average of 38.400 GWhe a year, and 1153,000 GWhe of base-load energy over its 30 yr expected lifetime [31]. In addition, 311,000 GWhe would be produced beyond the base output of 4.8 GWe. This energy can either be used to meet peak demand or sold to other utilities. If we define $P_b$ to be the rated steady state power of the combined system, then the capacity factor defined by equation (6) represents the fraction of time that the system can meet this output. Figure 9 shows how this varies with the desired steady state output.

A 2010 estimate put the cost of installing a commercial size rooftop photovoltaic array at $\sim$4.59/Wp [61]. Assuming a 14.5% efficient module, the 297.5 km$^2$ PV array would cost $\sim$197 billion. The costs are expected to drop to $1.99$/Wp by 2020 [61], bringing costs to $\sim$85.7 billion. While these numbers are high, the base-load energy produced by this system would have an average cost of $\sim$0.206 $/kWh$ over a 25 yr period. If the excess energy were also included, the energy cost would drop to $\sim$0.162 $/kWh$. These prices are on par with the current residential electricity prices in Japan ($\sim$0.241 $/kWh$ in 2010 [62]). Such a system would require high upfront costs, however if Japan is to phase out nuclear power, some form of new power systems must be built, with an expected cost of $84$ billion for coal or natural gas plants, above [9]. In addition, previous work has shown that the costs of photovoltaics are expected to drop as production increases [55].

If TEPCO wanted to completely replace their full nuclear capacity with solar power, and achieve a capacity factor equivalent to its own historical maximum of 0.84 (supplemental information available at stacks.iop.org/ERL/8/2014042/mmedia), it would require an array at least 5.6 times larger than the currently available roof area in Kanto. Arrays as large as 1.8 km$^2$ have been built in the United States [63], but ones at the scale needed here have not yet been attempted. This would require either the construction of new pumped hydro facilities, purchasing storage from other utilities, or the use of battery, compressed air, or other storage mechanisms.

Determining how to optimally provide power requires a balance between storage capacity and array size. If less than 24 h of storage were available, an array sized such that the minimum irradiance would provide enough energy to supply the base-load would suffice. However, this system would be massively overbuilt and would produce a large amount of excess energy. Alternatively, a much smaller array would be

| Parameter                              | Value               |
|----------------------------------------|---------------------|
| Array size                             | 297 km$^2$          |
| Storage capacity                       | 7.28 GW             |
| Fraction of base-load capacity, $P_b$  | 4.8 GWe             |
| Capacity factor, $CF$                  | 0.909 ± 0.017       |
Figure 8. Variability of power production over 25 yr. (Top) The figure shows the fraction of base-load demand, $f_P$, not met by solar power for each month during the studied period. The system being considered would have been able to provide $\geq 63\%$ of this base-load level throughout the year. (Bottom) However, it is likely that with such a system, regular maintenance would be scheduled during the less productive winter months. The figure shows the number of consecutive days solar power was unable to meet demand. Tokyo is likely to have less than 5 d in a row in which solar power cannot completely provide for 26.5% of its nuclear capacity.

Figure 9. Capacity factor as a function of power continuously provided per day. Here $f_P$ is the fraction of Tokyo’s base-load power that would be provided by the combined system. The capacity factor is defined by equation (6) and represents the fraction of the days per year for which power output could be met. The proposed solar system can meet a demand of 3 GW with a capacity factor of 1.0. The black line shows the US average nuclear capacity factor, 0.91. The proposed system could provide 4.8 GW with this capacity factor. The red line shows Japan’s peak nuclear capacity factor, 0.84, which this system would meet if providing 5.6 GW.

necessary if a large storage facility were available, such that all energy from the array could be stored long term for later use. Realistically, an optimum can be found based on the parameters of the location and whether the area is limited by the total storage capacity or the area available for the solar arrays [45].

Before the Fukushima accidents, nuclear power provided for more than the base-load electricity needs of the Kanto region. Even at 297.5 km$^2$ a distributed PV array in greater Tokyo would not exceed the power output of the nuclear fleet a small fraction of the time, figure 10, let alone the demand for greater Tokyo [64]. The energy from a distributed PV system would simply go directly to the grid. However, if countries such as Japan look to replace their use of nuclear power with renewable resources, it will be necessary to utilize these intermittent resources as more than just a way of helping to meet peak demand. Alternatively, if the system is being
optimized to reduce the overall carbon signature of electricity production, then the round-trip losses associated with pumped hydro storage would require that the energy stored come from the source with the lowest carbon signature. In Japan, in the absence of nuclear power systems, this would likely be power from PV.

4. Conclusions

We have analyzed the potential for using the available rooftop area in the Kanto region of Japan as a base for a distributed photovoltaic system that could help provide base-load electricity for the region. We estimated that a total area of 297.5 km$^2$ is currently available. When coupled to the 7.28 GW of pumped hydroelectric storage owned by TEPCO, the combined system was found capable of providing 4.8 GWe of 1700 km$^2$, coupled to 18.1 GW of storage capacity would be sufficient to replace TEPCO’s 2010 nuclear capacity.

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