Scenario analysis of the nuclear power's role in future zero-carbon electricity system in Japan

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Abstract: The realization of a zero-carbon electricity system is of vital importance to a future zero-carbon energy system and society, and nuclear power is expected to contribute to this much more than intermittent, complicated and costly renewable energies in the future in Japan. Therefore, in the present study, the role of nuclear power in Japan's future zero-carbon electricity system was studied using scenario analysis methods. Furthermore, technical feasibility analysis was conducted for electricity systems of the proposed scenarios in terms of reliability for the fluctuations of both daily and seasonal electrical demand and supply using an hour by hour simulation. The results show that nuclear power will contribute at least 60% of electricity production, and the whole systems were proven to be technically feasible with the help of EV batteries and hydrogen for daily and seasonal electricity storages respectively, operated based on smart gird control technologies.

Keyword: nuclear power; zero-carbon; electricity system; electric vehicle (EV); hydrogen; smart grid

1 Introduction

The CO_2 emission reductions required for low/zero carbon future could be achieved mainly in three different ways: by a reduction in energy demand, an expansion in nuclear power or an increase in renewable energy production. Several studies show that this reduction could also be achieved by increasing the share of electricity utilization at end-user side [1-2], which is considered to be the most effective way to reduce demand through technology substitution and energy saving, and increase the penetrations of nuclear power and renewable energy simultaneously. The philosophy adopted in this study agrees with these studies and considers that society is becoming more reliant on electricity, and thus further highlights the need to move to a zero-carbon electricity system based on zero-carbon power sources including nuclear power and renewable energies (Photovoltaic (PV), wind, biomass, *etc.*).

Although some future zero-carbon energy system scenarios based on renewable energy (solar, wind, wave, *etc.*) have been proposed both for individual countries or globally [3-4], the most common criticism is that renewable energies produce electricity too intermittently and too costly. Thus, nuclear power is expected to contribute to zero-carbon electricity production much more in the future in Japan [1-5]. Therefore, in the present study, two extreme scenarios for zero-carbon electricity systems with maximum and minimum nuclear power share were proposed and their feasibilities were examined, to highlight the role of nuclear power in the whole system. The scenario analysis is conducted in two steps, the nuclear power share in the mix of the zero-carbon electricity system is proposed in the first step; and technical feasibility of the whole system is studied in terms of reliability for demand-supply balance in the second step.

The results show that nuclear power will contribute at least 60% in terms of electricity production in a future zero-carbon electricity system, and the whole system is confirmed as technically feasible with the help of EV batteries and hydrogen for daily and seasonal electricity storage respectively operated based on smart grid control technologies.

2 Design of future zero-carbon electricity system

2.1 Electricity demand

The electricity demand is predicted that by the year 2100 total final energy demand in Japan will be almost reduced by half compared to that of 2005 [6]. However, due to the increased electricity utilization in general, demand would actually increase and

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become about 1.5 times greater than at present, going from 990TWh to 1400TWh, meaning the electrification ratio would triple from 25% to 75% [6].

The assumed hourly electrical load data is shown in Fig. 1 for the 8760 hours that make up one year. This figure includes some load levelling methods, such as demand side management, heat pumps and so on. For example, the temperature control at the end user side can effectively reduce the air-conditioner created electricity demand peak in summer. Therefore, all of these methods could lead to changes in the load factor of the electricity system, which is therefore increased to 65% compared with 60% at present without considering the impacts of Electric Vehicle (EV).

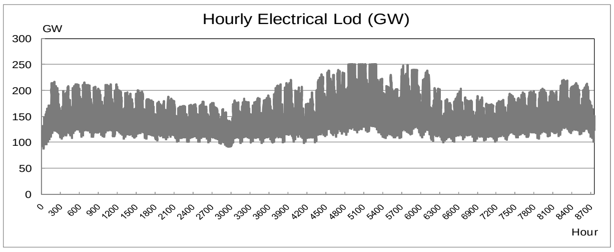

Fig.1 Assumed electric hourly load data series.

2.2. Operation pattern of nuclear power plants

Some studies on load-following of nuclear power stations thus far conducted indicate that some nuclear power plants have the capability to go from 100% of rated power down to 50% of rated power in a few hours [7]. This is useful for overnight load-following. However, the operation in a load-following mode would lead to lower economic performance, more frequent maintenance and increase of risks associated with operations [5]. Therefore, in the present study, the output power of nuclear power plants is considered to be adjustable on a monthly basis as decided by periodic inspection and maintenance schedules based on the publications of Tokyo Electric Power Company [8].

With a constant rating of thermal output nuclear power, the capacity factor can reach 110% according to historical test data [9]. Therefore, in the present study, the average maximum monthly capacity factor of nuclear power is considered to be 105%. On the other hand, with potential future efficiency enhancement resulting from improvements in periodic inspections and safety, the minimum monthly capacity factor for nuclear power is considered to increase to 75% from 60% at present.

2.3. Proposal of electricity mix

The Japanese government keeps "The Country Depends on the Nuclear Power" as one of its basic energy policy principles by saying that nuclear power is indispensable for both energy security and the realization of zero-carbon electricity system. In order to meet the annual electricity demand at 2100 (*i.e.*1400TWh) as described above, two zero-carbon electricity system scenarios with maximum and minimum nuclear power, respectively, are proposed in the present study.

The electricity production of a power plant is decided by its install capacity and capacity factor. The Scenario 1 is based on 100% nuclear power. However renewable energies are introduced as much as possible in the Scenario 2 according to their potential estimations [10]. For the penetration rates of renewable energies, it is necessary to consider not only the physical constraints including available space, solar irradiation, wind speed and available biomass source but also the reliability of the whole system [10]. Therefore, the install capacities of nuclear power can be obtained in two scenarios according to the supply-demand balance of electricity. As shown in Table 1, capacity factors of nuclear and renewable energies are stipulated, and the total grid loss is assumed to be 5%. And then the electricity generation mixes of two scenarios are obtained finally.

Table 1 Install capacity mix of scenario1&2 (S1&S2)

	Nuclear	Hydro	PV	Wind	Biomass
CF	90%	40%	12%	20%	75%
S1	185GWe	0	0	0	0
S2	120GWe	30GWe	100GWp	50GWe	30GWe

CF: Annual capacity factor

3 Short-term and long-term electrical load fluctuations and associated storage methods

The electrical load often changes in an electricity system, depending on the time of day and season. If electrical load-levelling between day and night and between different seasons can be achieved by storing electric power, it would be possible to achieve a high capacity utilization rate for nuclear power plants.

3.1 Short-term electricity storage

For a nuclear power based zero-carbon electricity system, the short-term diurnal fluctuations can be absorbed by using batteries which may supplant pumped hydropower eventually due to expected cost reductions in batteries [11-12]. Hence, electric vehicles could serve not only to alleviate CO_2 emissions from transportation but also work as batteries for the proposed nuclear power electricity system. If a high penetration of electric vehicles eventuates as proposed in previous studies, EV can use the excess nuclear power at night to charge their batteries (known as grid-to-vehicle or G2V), which would then be discharged during the day (vehicle-to-grid or V2G) [13-14].

It is assumed that there will be 35 million electric vehicles in 2100 in Japan (which would be half of the current vehicle fleet, and as by this time the population of Japan is projected to also halve due to low birth rates and an aging population) [6]. Each car is assumed to have a battery of 50kWh storage capacity, implying 1750GWh storage capacity in total. In addition to the storage capacity, another critically important factor is the state of charge (SOC) of the batteries. The SOC is defined as the ratio of the energy stored in a battery to the capacity of the battery. It varies from when the battery is fully discharged to when the battery is fully charged (expressed in percentages as a variation from 0% to 100%), and provides a measure of how much energy is stored in the battery.

As the batteries in EVs would serve the dual purpose of both storing electricity and powering vehicles, they would be more economically feasible as compared with those dedicated exclusively for electricity storage. Furthermore, the cost of batteries for vehicles is predicted to reduce significantly in the future.

3.2 Long-term electricity storage

Apart from the load fluctuations between day and night, long-term seasonal fluctuations also need to be considered [15]. Japan has a temperate climate with four distinct seasons. Electricity consumption is particularly high in winter and summer due to the high usage of air-conditioning units for cooling and heating, and hence the annual load factor is currently around 60% on average, which is lower than the 70% to 80% which is typical in Europe. This is also one of the biggest bottlenecks that currently prevent more widespread use of nuclear power utilization [16]. Any future electricity system based on nuclear power must take these variations into account, by utilizing excess capacity to produce an electrical storage medium which can be used to help nuclear power provide enough capacity to meet electricity demands during the peak seasons. Hydrogen in particular could be a good storage medium for surplus energy, as it can be stored for long periods as a liquid in tanks at high pressure and low temperature and could converted back to electricity to meet seasonal peak power demand by using various custom-made fuel cells [17, 18].

The storage and transportation facilities for Liquefied Natural Gas (LNG) already existing in Japan could be used as the basis for the hydrogen system. This would require some modifications, but the similar basic properties of LNG and liquefied hydrogen would make such a conversion relatively easy. In 2008, there were 27 LNG terminals with about 15 million m^3 storage capacities in Japan [19], and the annual LNG consumption in Japan was about 70 million tonnes. Hence, taking density into account [18], a peak of 1 million tonnes of hydrogen could be stored using the current storage capacity. If the same storage-consumption schedule of LNG is used for hydrogen, a total of about 12 million tonnes of hydrogen (an equivalent of 400TWh using 120MJ/kg as the LHV of hydrogen) could be contained and transported.

3.3 Comprehensive operation strategy for electricity storage using batteries and hydrogen

Conceptually, once plugged into the grid, EV batteries could be used as electricity suppliers. However, the maximum capacity of a typical EV battery is rather small and hence it cannot make any impact on the grid on its own. At the grid level, an EV appears simply as noise in the power system. For

EVs to be a useful resource, a certain degree of aggregation is required to bring about a size that can make a significant contribution to the grid. On the other hand, if too many EVs that are connected to the electricity grid to charge or discharge simultaneously, the electricity grid could be severely damaged. Furthermore, the electricity storage using batteries and hydrogen needs to be well coordinated, in order for the whole system to be reliable. Thus it is necessary that all of these electricity resources, batteries in EVs, hydrogen production, storage and transportation facilities and fuel cells can be controlled in real-time by an intelligent grid as shown in Fig. 2.

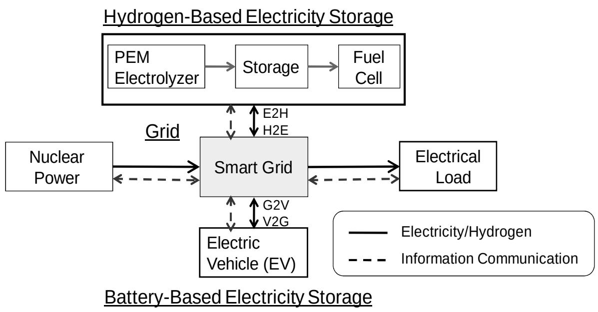

Fig.2 Schematic diagram of a zero-carbon electricity system based on electricity storage and smart control technologies.

Using the smart real-time control technology, a comprehensive electricity storage operation strategy can be realized as shown in the central part of Fig. 4. In this operation strategy, if the battery absorbs energy, the EV acts as a demand-side resource. If it releases energy, then the EV acts as a supply-side resource. The value of the SOC metric is used as the decision determinant to optimize the performance and also to decrease the battery degradation, and thus the charger of an EV battery stops drawing current when the SOC reaches 95%. Any excess electricity will then be used to produce hydrogen due to the fact that batteries have much higher efficiency for electricity storage and charge/discharge more quickly than fuel cells. But if the excess electricity is beyond the capacity of hydrogen production, any extra electricity will not be used by the system. The tolerance level of batteries in the present system is stipulated to be equal to an SOC value of 60%. This tolerance level is quite important, and during the discharging process, battery use is preferred over fuel cells when the SOC is higher than this tolerance, as batteries release electricity more easily in this state. On the other hand, when the batteries are below the tolerance level, they would only be used to cover for large gaps between supply and demand that fuel cells are not able to cover as the power output of batteries can be adjusted through control of the discharge length while fuel cells cannot. When the SOC of a battery reaches 30%, which is stipulated as the discharge depth, further discharge of battery is not permitted to avoid its degradation due to over-discharging. Such rules can extend battery life quite considerably; help to avoid inconvenience of having a car that is out of electricity when you need to drive; and also increase the capacity factor of fuel cells and thus their economic performance.

4 Feasibility analysis using a hour by hour simulation method

4.1. Simulation method

The hour by hour simulation method is shown in Fig. 3. The detailed simulation execution process is shown in Fig. 4. When the basic parameters including the monthly capacity factor of nuclear power, hydrogen production capacity and fuel cell capacity are defined, the simulation starts by reading the hourly electrical loads and power generation (nuclear, PV, hydro, wind, biomass) data records. Then the comprehensive electricity storage strategy subroutine described in the previous section is executed. If no deficiencies appear in the power supply, the system is considered as feasible and the program ends. Otherwise the basic parameters need to be redefined and a new simulation round is started, with this process being repeated until a feasible configuration is attained.

In order to evaluate the performance and reliability of the designed nuclear power based electricity system, two parameters are employed. One is the deficiency of power supply probability (*DPSP*), while the other is the relative excess power ratio (*REPR*). *DPSP* is used to evaluate the possibility of a deficiency in the power supply which can be calculated as per Eq. (1), and the *REPR* is given as a ratio of the total annual excess power generated by the system, as expressed in Eq. (2). Here the TEL is the annual Total Electrical Load; E_L and E_G are the hourly electrical load and power generation; E_{G2V} and E_{V2G} represent the charge and discharge of batteries in EVs; E_{E2H} and E_{H2E}

represent the transforming between electricity and hydrogen.

$$DPSP = \frac{DPS}{TEL} = \frac{\sum_{i=1}^{8760}(E_L - (E_G + E_{V2G} + E_{H2E}))_i}{\sum_{i=1}^{8760} E_{Li}} \tag{1}$$

$$REPR = \frac{REP}{TEL} = \frac{\sum_{i=1}^{8760}(E_G - (E_{G2V} + E_{E2H} + E_L))_i}{\sum_{i=1}^{8760} E_{Li}} \tag{2}$$

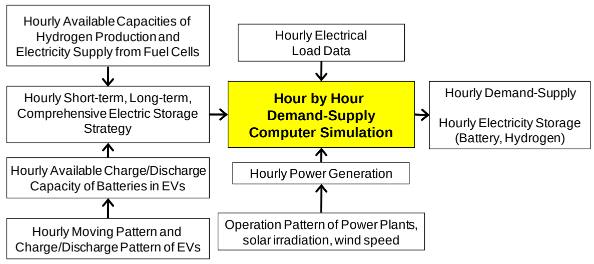

Fig.3 Hour by hour simulation method for feasibility analysis on zero-carbon electricity system.

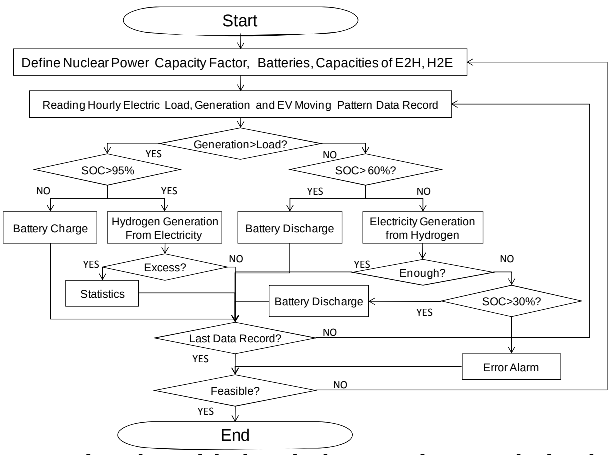

Fig.4 Flow chart of the hour by hour simulation method with the comprehensive electricity storage strategy.

4.2. Results

The hourly electrical supply-demand balance relationship and the electricity storage operation information in Scenarios 1 and 2 were obtained using the developed computer software code as shown in Figs. 5 and 6, respectively. The results show that during the spring and autumn periods, and some week-long Japanese holidays such as the New Year Festival (beginning of January), Golden Week (beginning of May) and Bon Festival (middle of August.), surplus electricity generated is converted to hydrogen through electrolysis of water when the EV batteries are in a "full" state. On the other hand, electricity is generated from hydrogen fuel cells in winter and summer when many electrical load peaks appear due to the heating and cooling service demands respectively. Hence during this period the hydrogen generated during the other periods must be converted back into electricity.

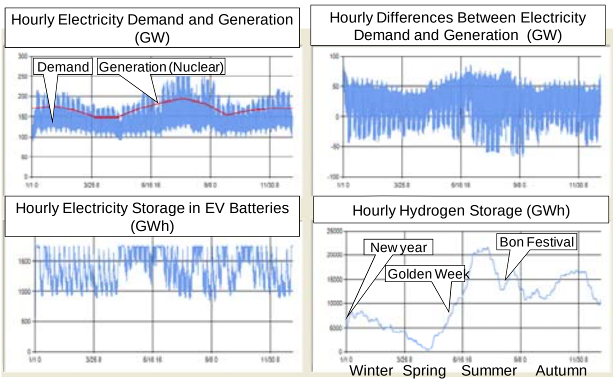

Fig.5 Hour by hour simulation results obtained using the developed computer code for one calendar year (Scenario 1).

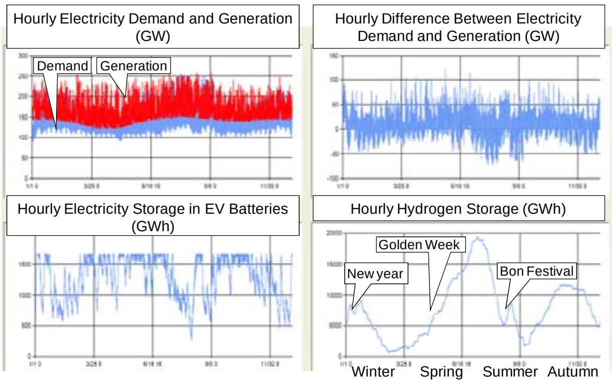

Fig.6 Hour by hour simulation results obtained using the developed computer code for one calendar year (Scenario 2).

The basic preconditions and operating pattern of nuclear power plants are shown in Tables 2 and 3, respectively. The obtained electricity mix is shown in Table 4. The results show that nuclear power will contribute at least 60% electricity production in the whole system with the help of storage using both battery and hydrogen by smart grid control.

Table 2 Basic parameters for electricity storage using batteries in EV and hydrogen

Parameter	Value
Efficiency of G2V	95%
Efficiency of V2G	95%
Number of EV	35 Million
Battery capacity of each EV	50 kWh
Batter full (SOC)	95%
Battery Discharge Depth (SOC)	30%
Efficiency of E2H	95%
Efficiency of H2E	60%
Total capacity of fuel cell	50 GWe
E2H capacity	70 GWe

Battery tolerance level (SOC)	60%

Table 3 Monthly capacity factor of nuclear power plants in scenarios 1&2 (S1&S2)

Month	S1	S2
Jan.	92%	100%
Feb.	95%	102%
Mar.	90%	90%
Apr.	80%	80%
May	90%	80%
Jun.	92%	92%
Jul.	100%	100%
Aug.	105%	105%
Sep.	99%	99%
Oct.	83%	85%
Nov.	89%	100%
Dec.	92%	105%

Table 4 Electricity mix of scenarios 1&2 (S1&S2)

	Nuclear	Hydro	PV	Wind	Biomass	Storage
S1	95%	0	0	0	0	5%
S2	60%	7%	7%	6%	15%	5%

Furthermore, the obtained detailed performance parameters are shown in Table 5, which shows that two scenarios of nuclear based zero-carbon electricity system are technically feasible for realizing an hourly electricity demand-supply balance with the help of storage functions provided by batteries and hydrogen. Compared with the Scenario 1 based on 100% nuclear power, the Scenario 2 should introduce 100 GWp PV and 50 GWe wind power in the electricity generation system. Because outputs of PV and wind power are highly dependent on natural conditions including solar irradiation and wind speed, the system may have more demand-supply fluctuations. Larger charge/discharge capacity is necessary in Scenario 2 than Scenario 1 to keep the reliability of the electricity system.

In the future study, some methods of output control of PV and wind power will be employed to reduce their output when there is too much surplus electricity appears. In the present study, the electricity storage capacity is given as the precondition of the study. Its optimization will be studied based on hourly data in future.

Table 5 Performance parameters of scenarios 1&2 (S1&S2)

Parameter	Value	
	S1	S2
Total G2V(TWh)	124.4	96.2
Total V2G (TWh)	45.5	18.7
V2G/TEL (%)	3.3	1.4
Max. G2V (GW)	74.1	99.2
Max. V2G (GW)	62.4	57.8
Initial H2 (TWh)	5	5
Max. H2 (TWh)	22	22.4
DPS (TWh)	0	0
REP (TWh)	0.33	0.63
Total E2H (TWh)	46.3	41.52
Total H2E (TWh)	24.8	23.58
H2E/TEL (%)	1.8	1.7
Max. E2H (GW)	70	70
Max. H2E (GW)	50	50
Final H2 (TWh)	10	8
Min. H2 (TWh)	0.3	1
DPSP (%)	0	0
REPR (%)	0.022	0.041

5. Availability of necessary resources

Apart from the supply-demand balance in electricity system, the availability of key resources also needs to be considered for realizing the nuclear power-based zero-carbon electricity system.

5.1 Nuclear fuel

In Japan, 50 GWe of nuclear power plants produced 260 TWh in 2009 using 8 thousand tonnes of natural uranium. Globally at the same time, there were 380GWe nuclear power plants operating and 2600 TWh electricity was produced using about 70 thousand tonnes of natural uranium [20]. The proven reserves of natural uranium are about 5.5 million tonnes in the world. Therefore, thus the R/P (Reserves-to-production) ratio of natural uranium was about 85 years at the end of 2009. However, the total Undiscovered Resources are anticipated to be 10.5 million tonnes which can sustain about 150 years at current usage levels [21].

However, the world demand for electricity is expected to continue to grow rapidly over the next several decades to meet the needs of an increasing population and economic growth. By the year 2030, the world's nuclear capacity is projected to grow to between about 509 GWe net in the low demand case and 663 GWe net in the high demand case. Accordingly, world reactor-related uranium requirements are projected to rise to between 94 and 122 thousand tonnes of natural uranium by 2030 [20].

On the other hand, either utilization of high enrichment uranium (above 5%) or nuclear fuel recycling can reduce natural uranium consumption by around 30%. Furthermore, 4.5 billion tonnes of natural uranium may be obtained from seawater according to some predictions [21], which can sustain 60 thousand years at the present consumption rates. FBR (Fast Breeder Reactor) can produce the same amount of electricity by using only 1% of LWR (Light Water Reactor) by the ideal conditions [20]. This would mean that the R/P ratio of natural uranium can be extended 100 times if all LWRs are substituted by FBRs. With the rapid increase of uranium price, other technologies such as extraction from seawater, recycling, and FBR could become economically competitive.

Apart from the availability of nuclear fuel, nuclear waste especially HLW (High Level radioactive Waste) needs to be eliminated. For that purpose, the ADSR (Accelerator-Driven Sub-critical Reactor) is expected to be used extensively in the future to burn MA (Minor Actinides) and produce electricity simultaneously [22].

5.2 Lithium resources

In the proposed zero-carbon energy system for Japan, there are 35 million EVs each of which uses a 50 kWh lithium battery array. But there are no lithium resources in Japan, hence import from overseas is necessary. Therefore, the global supply-demand balance situation needs to be considered to warrant the importation from overseas. According to the medium prediction by UN, the population of world will become 9 billion by 2050 which will be 34% increase to be compared with that of 2009 [23]. If the increase ratio is assumed as 10% from 2050 to 2100, then the population will reach 10 billion. If the penetration ratio of vehicle is 60% which means 100 people have 60 vehicles in average in the world [24], there will be 6 billion vehicles in total. If one vehicle is equipped with a 20kWh lithium battery in average, and 1kWh lithium battery needs 0.5kg of lithium, then in total 60 million tonnes of lithium will be necessary. However, there are only 10 million tonnes of reserves and 25 million tonnes resources on land [25], of which perhaps 50% can be used for lithium battery of electric vehicle [26]. Obviously, the lithium resource on land in the world is not adequate; therefore, extracting lithium from seawater is anticipated. According to various predictions, 230 billion tonnes of lithium is contained in seawater. Therefore, in order to realize the proposed zero-carbon energy system scenario in this study, most lithium resources need to be obtained from seawater.

6 Conclusions

In the present study, scenario analysis methods were used to study the role of nuclear power in future zero-carbon electricity systems. Two zero-carbon electricity scenarios were proposed to meet the given electricity demand. One was maximum nuclear power; the other was maximum renewable energy. The technical feasibility of the proposed scenarios was confirmed by conducting hour by hour simulation.

The obtained results show that nuclear power will contribute at least 60% of electricity production. However, both of batteries and hydrogen are necessary to absorb daily and seasonal fluctuations of demand-supply balance in the electricity system. Furthermore, in order to realize the proposed zero-carbon electricity system scenario, Japan needs to import nuclear fuel and lithium resource from overseas or extract them from seawater, and to develop new nuclear power technologies to guarantee long term availability.

Nomenclature

EV: Electric Vehicle
G2V: Battery charge from grid to EV
V2G: Battery discharge from EV to grid
E2H: Producing hydrogen by water electrolysis
H2E: Power generation from hydrogen fuel cell
LNG: Liquefied Natural Gas
LHV: Low Heat Value
HHV: High Heat Value
SOFC: Solid Oxide Fuel Cell
PEM: Proton Exchange Membrane

TEL: Total Electrical Load
SOC: State of Charge
REP: Relative Excess Power
REPR: Relative Excess Power Ratio
DPS: Deficiency Power Supply
DPSP: Deficiency Power Supply Possibility
CF: Capacity Factor
ADSR: Accelerator Driven Sub-critical Reactor
FBR: Fast Breeder Reactor
MA: Minor Actinides

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