Future zero-carbon energy systems in Japan with different nuclear power development scenarios

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Abstract: An integrated scenario analysis has been conducted toward zero-carbon energy system from 2010 to 2100 in Japan, wherein the effect of Fukushima nuclear accident happened in March, 2011 is more or less taken into account. In the study, various service demands are firstly estimated based on social-economic data and then best technology and energy mixes are obtained using the optimization model to meet the service demand. On the conductance of integrated scenario analysis towards the year 2100 when zero-carbon energy system will be attained, three different scenarios of nuclear power development are taken, *i.e.*, (i)no further introduction of nuclear, (ii) fixed portion and (iii) no limit of nuclear. The results show that, in the end user side, zero-carbon energy scenario can be attained at 2100 with electricity supplies 75% of total energy utilization. And for the electricity supply, three different power generation scenarios are proposed: (Scenario 1) 30% renewable and 70% gas-CCS(Carbon Capture and Storage), (Scenario 2) every one third by nuclear, by renewable and by gas-CCS, and (Scenario 3) 60% nuclear power, 20% renewable and 10% gas-CCS. Lastly by the inter-comparison of the three scenarios from the four aspects of cost, CO_2 emission, risk and diversity, Scenario 2 is rated as the most balanced scenario among the three by putting emphasis on the availability of diversified electric source of nuclear, renewable and gas-CCS.

Keyword: zero-carbon energy system, scenario analysis, nuclear power

1 Introduction

Carbon dioxide (CO_2) and other greenhouse gas (GHG) resulting from fossil fuel combustion contribute to the rise of global temperatures and to climate change. Humanity has to decide whether business as usual should continue further or some concerted action should be taken to reduce CO_2 emissions.

To cope with this global warming, Japanese policy makers need to clearly understand the level of the required commitment. The required CO_2 emission reductions could be achieved mainly by three different ways: (i) reduction of energy demand, (ii) expansion of nuclear power, and (iii) increase of renewable energy.

According to the Japanese governmental reports [1-2] published before Fukushima Daiichi accident in March 2011, the energy policy planning in Japan considered that future society towards 2100 should rely more on electricity, and that it should further move to a zero-carbon electricity system based on zero-carbon power sources including nuclear power and renewable energy. It was assumed that the increased electricity utilization of energy usage in the end-user side is the most effective way to reduce energy demand through technology substitution and energy saving as well as by the increase of nuclear power and renewable energy simultaneously.

The authors of this paper had engaged in the research project at Kyoto University in Japan which aimed at developing a comprehensive methodology of integrated scenario analysis for future zero-carbon energy system to be applied to assess the role of energy efficiency, structural change in industry, and new supply options for transforming Japanese economy to a lower-GHG trajectory in the longer term, and they also applied the developed methodology to evaluate the plausible energy policy options in Japan spanning towards 2100.[3-8]

The project at Kyoto University was already finished in 2012. And it is noted that East Japan Earthquake happened in March 11, 2011.The scenario analyses conducted by the project members of Kyoto University took into account of the effect of East Japan Earthquake. Therefore, it is considered to be worthwhile to introduce the results of this project done at Kyoto University because the developed analysis methodology itself will be applicable for the Japanese energy scenario even for its post-Fukushima era.

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In which follows, the overview of the developed energy scenario analysis will be given in 2, the result of scenario analysis in 3, followed by the concluding remarks.

2 Method

An integrated energy scenario analysis model has been developed as shown in Figure 1. It is composed of three parts: (1) bottom-up simulation model, (2) long-term generation planning model, and (3) hour-by-hour simulation model.

The first model (1) will give the final energy demand based on the information of macro-economy, lifestyle, industrial structure and technology improvement. Both annual electricity demand and electric load duration curve are also obtained from this step of (1). The second model (2) is an optimization model for conducting power generation planning to meet with the electricity demand being subjected to various constraints including natural resources, economic, environmental, geographic, natural conditions, etc. The third model (3) is an hour-by-hour simulation model for testing the reliability of the obtained best mix of power generation by considering the integration of renewable energy and smart grid strategy.

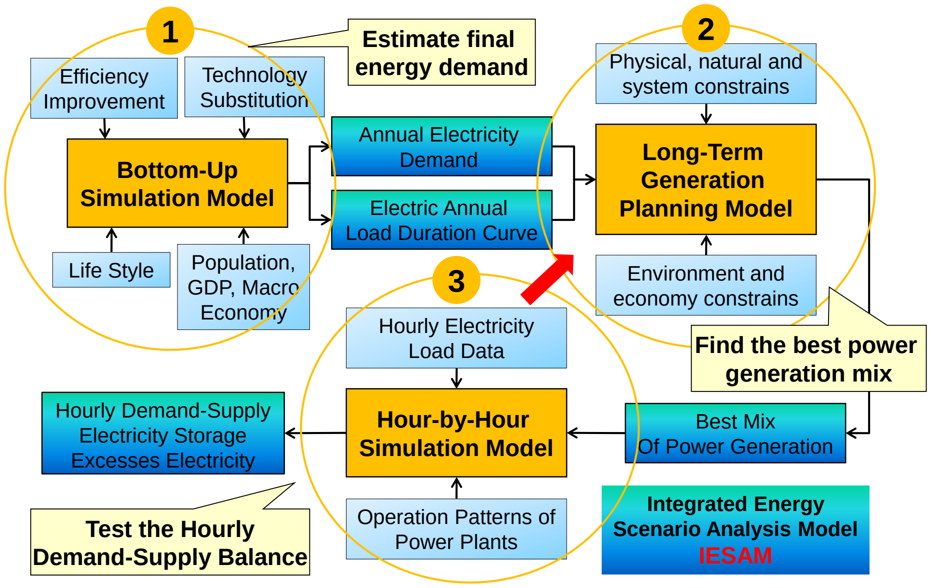


Fig. 1 Proposed integrated scenario analysis model.

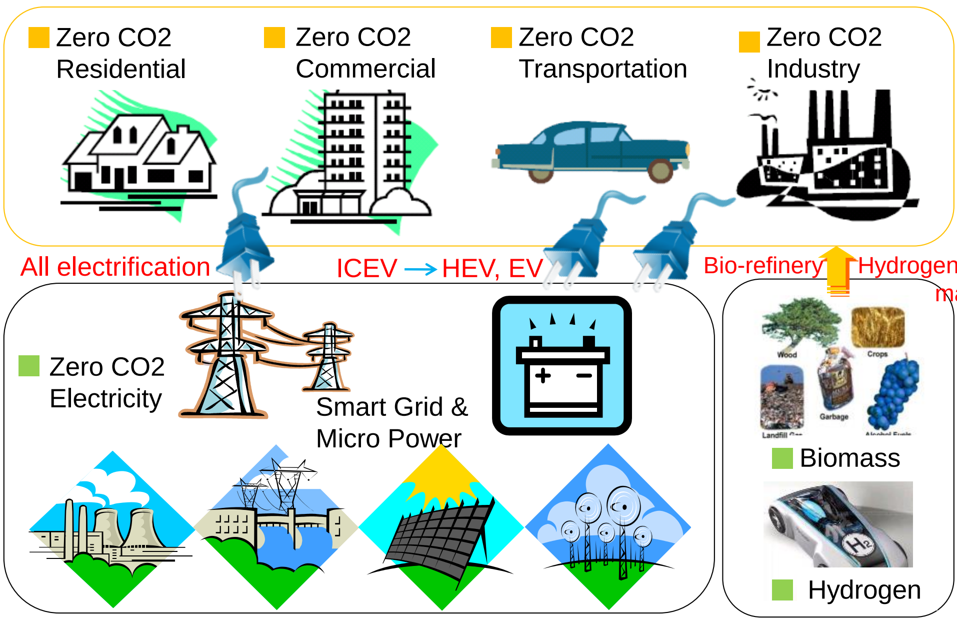


Fig. 2 Electricity-based future zero-carbon energy system.

3 Scenario analysis

The proposed methodology of integrated scenario analysis model as mentioned in Section 2 was applied to evaluate the zero-carbon energy scenario of Japan to be accomplished in 2100. In which follows, the assumed electricity-based future zero-carbon energy system is first given in 3.1, the obtained final energy demand in the designed scenario in 3.2, the three scenarios of electricity generation mixes in 3.3 with different nuclear power development scenarios, and the inter-comparison of three different scenarios in 3.4.

3.1 Assumed electricity-based future zero-carbon energy system

In this scenario analysis, the image of electricity-based future zero-carbon energy system is as illustrated in Figure 2. As shown in Fig.2. It is assumed that the future end-users in residential, commercial, transportation and industry sectors will use more and more electricity to reduce CO_2 emission. For example for the transportation by car, Inter-Combustion Engine Vehicle (ICEV) in these days will move more and more to Hybrid Engine Vehicle (HEV) and Electric Vehicle (EV) in future with technical progress.

On the other hand of end-user side, it is also assumed that the energy-supply side will use renewable, nuclear and clean thermal power to provide zero-carbon energy generations. And in some parts of industry, biomass will be used as rural material and hydrogen as heat source.

3.2 Obtained final energy demand in the designed scenario

A scenario analysis of zero-carbon energy system toward 2100 by the developed integrated analysis model resulted in the final energy mix trajectory until 2100 as shown in Figure 3. As seen in Fig.3, coal, oil and gas should be decreased gradually in order to meet with zero CO_2 emission in 2100. Therefore, electricity, hydrogen and biomass will become the major sources of energy in 2100. Although the total energy consumption will decrease to 65% in 2100, the electricity demand is expected to keep at the same level of 1000TWh from 2010 to 2100, while the increase of electrification ratio from 25% in 2010 to 75% in 2100.

The above stated result was obtained with the prepositions of (i) all electrification in residential and commercial sectors, (ii) use of electric vehicles, bio-fuel airplane, *etc.* in the transportation sector, and (iii) hydrogen steel making, bio-refinery for new material, eco-cement making, paperless office, *etc.* in the industrial sector, in order for the end-user side to satisfy zero-carbon energy scenario. The obtained final energy mix shows that zero-carbon electricity generation system is of vital importance to the achievement of zero-carbon emission energy system in the future when the society becomes more and more reliant on electricity.

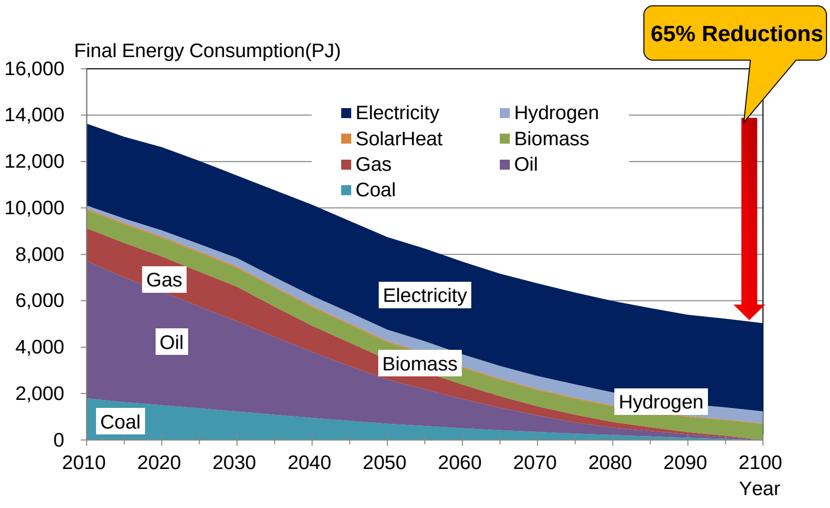


Fig.3 Final energy demand in the design scenario.

3.3 Three power generation mix scenarios

Then how the electricity generation would be for the future of Japan? As already mentioned in the part of introduction, the authors assumed three different scenarios by changing the role of nuclear power in the future energy scenario in Japan. For the first scenario (Scenario 1), no new nuclear power plant is built since 2010. On the other hand, for the second scenario (Scenario 2), new nuclear power plant is permitted but the maximum capacity is limited to 50 GWe, while for the third scenario (Scenario 3) no specific constraints are assumed for nuclear power.

In the author's analysis of Japanese future electricity scenario from 2010 to 2100 with time span of 5 years, it is one of the big uncertain issues how the effect of Fukushima Nuclear Accident happened in March 11, 2011 should be taken into account. However, in this presented analysis of energy scenario, we assumed that in Scenario 1 that the four destroyed nuclear units of Fukushima Daiichi plant will be decommissioned in 2011 and all other nuclear units will be decommissioned within their lifetime of 40 years, and thus_the other remaining units in Japan will continue to operate with the total output about of 50 GWe, even after Fukushima accident. In reality, all 50 nuclear units in Japan have been still dormant in the year of 2014. There will be the possibility of several nuclear power units will restart within 2014, but it is not foreseen all units can restart again in the near future by several reasons. Also for Scenario 2, construction of nuclear power plants in new sites will be canceled and only the rebuild of old plant at the original place is permitted. This is the reason why nuclear power will be restricted less than the 50 GWe level of the year 2010.

(This nuclear scenario may also not be so feasible in Japan after Fukushima accident.)

The obtained three power generation mix scenarios are shown in Figure 4 (a), (b), and (c) respectively for Scenario 1, 2, and 3.

Prior to the discussion on the inter-comparison of the three scenarios, the author will answer several questions which might arise by seeing the graphs in Figure 4.

(i) What is the reason for the flat curve of nuclear in Scenario 2?

The reason why nuclear power will keep constant level of the upper limit of 50GWe for almost all span until 2100 is because nuclear is the best choice from cost and free CO_2 gas discharge.

(ii) What is Gas-CCS? And why the gas CCS always comes later than gas in all three scenarios?

Gas-CCS means Gas power with CCS (Carbon Capture and Storage) equipment. The implementation of this technology under development is decided by the least-cost optimization model for generation expansion, and the result is that it should be in any scenario developed as late as possible, to be compared with the competing technologies of coal or gas power. This is because of the higher cost of CCS equipment installation and operation.

(iii) Why nuclear decays to zero until 2050 in Scenario 1?

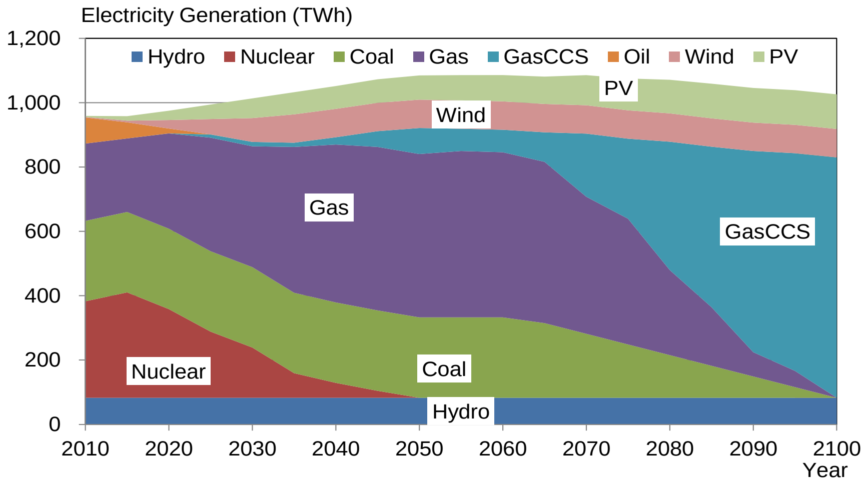
Since no new nuclear power plant can be built or replaced in Scenario 1, the number of retiring plants will increase year by year, with the maximum life of nuclear power plant being assumed to be 40 years. Therefore, nuclear power will completely phase out by 2050.

(iv) Why hydro always flat in all scenarios?

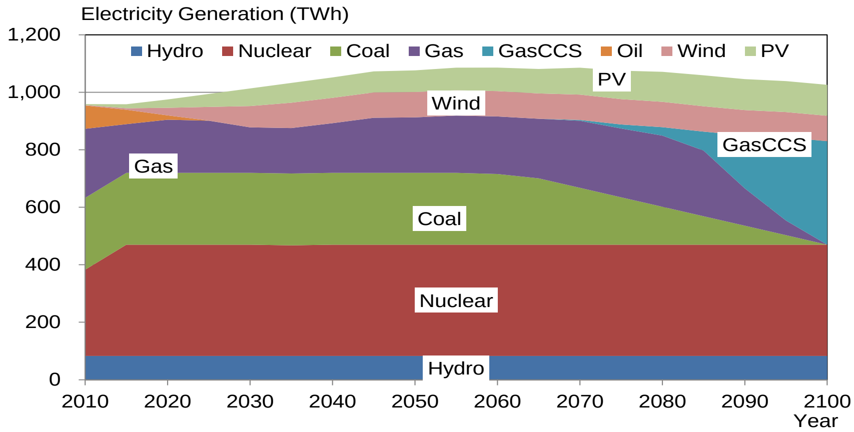
The potential of hydropower development in Japan is already very limited and thus we assume that its capacity will keep constant [2].

(vii) Why nuclear becomes flat after 2050 in Scenario 3?

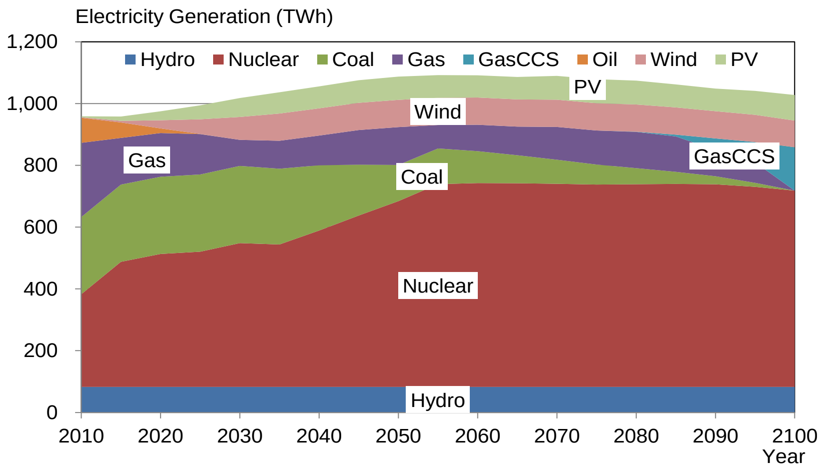
The power generation capacity and generation amount are calculated by the least-cost optimization model. It is subject to various constraint aspects such as resource, technology, economy, environment, *etc*. However, the nuclear will not become so flat after 2050. It will still change rather slowly and slightly. As mentioned before the nuclear power generation is decided by many constraints, for example, (a)nuclear power plant cannot be built so fast due to the manufacturing and building capacities; (b) nuclear power cannot be developed so fast due to the space constraints and lead-time; (c) PV and wind must achieve their developmental goal according to the energy policy to prioritize the introduction of renewable energy definitely; (d) gas and coal power plant will generate power when their capacity is not zero in order to reduce new capacity requirements which is much more expensive when the objective function is least-cost; and (f) the most important is that the energy system will need some fast start-up power source such as gas power to absorb the fluctuations of PV and wind power. The last factor (f) is also the reason that gas power will remain in any scenario.



(a) Scenario 1 (no new nuclear since 2010)



(b) Scenario 2 (maximum 50 GWe for nuclear power)



(c) Scenario 3 (no specific constraints for nuclear power)

Fig.4 Electricity generation mixes in three scenarios 1, 2, and 3 with different nuclear power development scenarios.

3.4 Inter-comparison of three different scenarios

From the viewpoint of inter-comparison of the three different scenarios, it is first seen from Figure 4 (a), (b), and (c) that in 2100 the electricity depends on 70% by gas in Scenario 1, 60% by nuclear by Scenario 3, while all 30% percentages for renewable energy, nuclear power and gas-CCS, by Scenario 2.

The inter-comparison of the three different scenarios was conducted by an integrated perspective by using a radar chart as shown in Figure 5. Three scenarios are evaluated from versatile aspects of economy, environment, risk and diversity aspects, by using total cost, accumulated CO_2 emission, Herfindahl-Hirschman Index (HHI) [9] and immediate fatality rates. In the present study, the risk of various kinds of power generation technologies is expressed by using immediate fatality rate, which is calculated based on the published data of fatality rate per GWe times operating year, for various types of power generation technologies [10].

As shown in Figure 5, all the data of the four indexes are standardized as normalized from 0 to 1, where lower number value of HHI for example means higher diversity. Therefore, for all the four indexes the smaller value the better performance.

It is seen from the result of Figure 5 that the Scenario 1 is the worst among the three. The scenario 3 is better than the Scenario 2 in both risk and CO_2 emission with equal in cost. The Scenario 2 is better than the Scenario 3 only the HHI; the diversity of energy source.

It is obvious that the state of Japan after Fukushima accident is the same as the Scenario 1: high cost, high CO_2 emission, less diversity and high risk. But after Fukushima accident there are a lot of people in Japan who fear radioactive contamination by nuclear accident so that they put highest priority to avert radioactive risk with the sacrifice of all other factors such as cost, CO_2 emission, and diversity.

In this research, the author assumed that the immediate fatality rate is risk. However, the notion of risk is versatile and each person has different notion of risk. Therefore, without the common agreement on the definition of risk, it is very difficult to judge what will be best scenario.

However, the project group members of Kyoto University who had been involved in this research on carbon-free energy system in Japan concluded that the Scenario2 is the best energy scenario for Japan towards 2100, by putting more emphasis of energy diversity and reserve nuclear energy option for no CO_2 emission and low cost with careful reserve of putting the umbrella of total nuclear capacity less than the present level with enforced nuclear safety by lessons of learned from Fukushima accident.

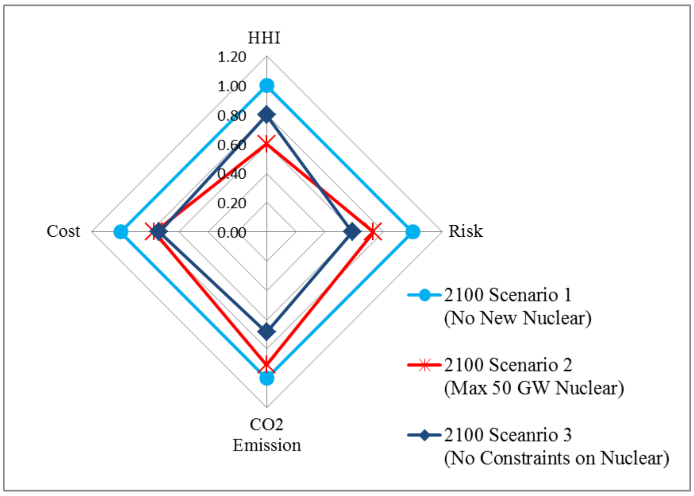


Fig.5 Inter-comparison of three scenarios for carbon-free energy system in 2100 in Japan.

4 Concluding remarks

An integrated scenario analysis was conducted toward zero-carbon energy system from 2010 to 2100 in Japan, wherein the effect of Fukushima nuclear accident happened in March, 2011 was more or less taken into account. In the study, various service demands were firstly estimated based on social-economic data and then best technology and energy mixes were obtained using the optimization model to meet the service demand. On the conductance of integrated scenario analysis towards the year 2100 when zero-carbon energy system will be attained, three different scenarios of nuclear power development were taken, *i.e.*, (i) no further introduction of nuclear, (ii) fixed portion and (iii) no limit of nuclear. It was pointed out that, in the end user side, zero-carbon energy scenario could be attained in the year 2100 with electricity supplies 75% of total energy utilization. And for the electricity supply, three different power generation scenarios were proposed: (Scenario 1) 30% renewable and 70% gas-CCS, (Scenario 2) every one third by nuclear, by renewable and by gas-CCS, and (Scenario 3) 60% nuclear power, 20% renewable and 10% gas-CCS. Lastly by the inter-comparison of the three scenarios from the four aspects of cost, CO_2 emission, risk and diversity, Scenario 2 was rated as the most balanced scenario among the three by putting emphasis on the availability of diversified electric source of nuclear, renewable and gas-CCS.

Nomenclatures

CCS:	Carbon Capture and Storage
HHI:	Herfindahl-Hirschman Index
PV:	Photovoltaic
ICEV:	Inter-Combustion Engine Vehicle
HEV:	Hybrid Engine Vehicle
EV:	Electric Vehicle

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