Technology evaluation of zero-carbon power generation systems in Japan in terms of cost and CO_2 emissions

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Abstract

To realize a low-carbon society, we identified the issues that need to be addressed to construct a zero-carbon power system in Japan. First, based on the estimation of future technology development, we constructed technology scenarios using the manufacturing technology database developed by the Center for Low Carbon Society Strategy (LCS). Second, the power system was evaluated using the optimal multi-region power generation model of cost minimization, considering system stability under various constraint assumptions. We found that, in addition to the limitations imposed by the technological development of renewable energy, grid enhancement and the system stability constraint have the greatest influence on power generation cost to achieve a zero-carbon power system. Furthermore, it was shown that, as the demand for electricity increases, it becomes difficult to achieve zero emissions, and the development of renewable energy technologies that contribute to system stability such as hot dry rock geothermal energy becomes important.

Keywords: Zero-carbon power generation systems, Grid system stability, Renewable energy technologies

1. Introduction

The use of renewable energy is rapidly expanding due to reduced costs of renewable sources and storage battery systems, but the electric power grid system will become unstable with the large-scale introduction of renewable energy. In particular, there is a concern that the inertial force, which was conventionally supplied by thermal power generation, will be insufficient to ensure system stability as renewable energy becomes the main power source. If the inertia force is insufficient, the frequency drops sharply and causes a large-scale blackout when the balance of supply and demand suddenly breaks down due to such as a ground accident. Several studies have evaluated power generation system costs and technical issues related to a large-scale introduction of renewable energy. The impact of increased SNSP (system non-synchronous penetration) is being evaluated in Ireland and other European countries[1-4]. On the other hand, there are few studies that simultaneously evaluate renewable energy technology (present and future), economic efficiency of large-scale introduction of renewable energy, and system stability including the effect of changing the amount of inertial power generation in the grid.

The Center for Low Carbon Society Strategy (LCS) has developed an optimal power generation model to evaluate power costs under CO_2 emission constraints, while considering the system stability. The model enables quantitative evaluation of renewable energy technology scenarios, including technological development issues under various future social scenarios. In previous studies, we have evaluated the economic efficiency of reducing electricity-originated CO_2 emissions by 80% or more under an electric energy demand of 1000 TWh/y at costs equivalent to current rates, and have shown the possibility of

using technology to achieve zero emissions[6-9]. In the present study, we evaluated the economic efficiency and technical problems of a zero-carbon power generation systems, considering electricity demand, system stabilization technology, and renewable energy technologies. First, based on estimations of future technology development, we constructed technology scenarios using the manufacturing technology database developed by the LCS. Second, the power system was evaluated using the optimal multi-region power generation model of cost minimization considering system stability under various constraint assumptions such as CO_2 emissions reduction rate, power demand, the technology level of renewable energy and storage systems, reinforcement of the transmission grid and grid stability constraints.

2. Methodology

2.1. Economic evaluation method with optimal multi-regional power generation model

In this study, we examined the relationship between electric power cost and CO_2 emissions of a power generation system having a high ratio of renewable energy, considering future technological developments. This methodology enables a quantitative estimate of the economic effects of technological development and identifies the issues inherent in achieving CO_2 emission reduction targets.

We evaluated the economics of low-carbon power generation systems under different technology scenarios, using an optimal multi-region power generation model which considers system stability. The evaluation method using the model developed by LCS has the following features. 1) Quantitative technology scenarios were developed that consider future renewable energy technologies. 2) Under the constraints of CO_2 emissions, the capacities of power generation systems, storage battery systems and hydrogen turbine systems were optimized as endogenous variables. 3) As constraint assumptions of system stability, in addition to supply-demand balance and short term fluctuation adjustment, we determined the fraction of the power system that can supply the inertial force necessary to overcome supply-demand imbalances as the transient stability constraint. Each feature is specifically described below.

2.2. Technology scenarios considering future technology development of renewable energy and storage systems

With regard to renewable energy technology, we used technology scenarios developed by LCS, which has analyzed the current and future technology and cost reduction potential for solar, wind, small and medium hydropower, biomass, geothermal power, and storage battery systems[9-12].

In this method, the costs of future renewable energy technologies are calculated for an estimated technology level including the index of performance, manufacturing technology etc. We aggregated the results of estimated costs of equipment, labor, raw materials, and utilities required for manufacturing each type of renewable energy power system based on the equipment database of LCS. Here, we estimated the technologies that could be realized by 2030 as technologies introduced and spread in 2050.

2.3. Model configuration and endogenous variables

This optimized multi-regional power generation model uses linear optimization programming and minimizes the total cost of power generation under the constraints of CO_2 emissions and power demand. The principal parameters of the model are the type of power supply, the amount of available battery storage, and the capacity of electrolysis and hydrogen turbines in the system, which are characterized by using these as endogenous variables. Carbon capture and storage (CCS), imported biomass and imported carbon free hydrogen are not included in this analysis. Japan is divided into 10 regions by the major electric power companies. In this model, power supply and demand levels were estimated using hourly data of power consumption in each region. The daily load curve was classified into seven representative

days according to the seasonal characteristics. Hourly output of photovoltaic (PV) and wind power generations were estimated using climate data for one year at several tens of locations around Japan. For inter-regional transmission, in addition to the use of existing transmission lines, the enhancement cost of transmission line capacity is estimated.

2.4. Constraint assumptions for stabilizing the grid system

With the large-scale introduction of renewable energy, it is necessary to implement load frequency control of short-term fluctuations in voltage and frequency, and mitigation of long-term seasonal fluctuations, both of which are currently performed by thermal power generation systems. In addition, the power output via an inverter such as a solar power generation system or a wind power generation system cannot provide an inertial force to stabilize the grid system. Therefore, it is also necessary to ensure the stability of the system to prevent a large scale blackout due to a ground accident etc.

Constraint assumptions on system stability include load frequency control (LFC) constraints and transient stability constraints in addition to supply-demand balance constraints. The supply-demand balance constraint is a constraint in which the amount of power consumed for each one-hour data period and the actual amount of power generation excluding losses are always balanced. The LFC constraint is one-hour fluctuation rate of renewable energy and demand by power source type and region. It is a restriction that calculates and supplies a degree of fluctuation suppression. A transient stability restriction is a one that sets the fraction of electricity supplied by synchronous generators (i.e., rotating steam and gas turbines) which can provide inertial force. It is referred to as the "inertia fraction", which is the rate of power output provided by synchronous generator, in this paper. At present, an inertia fraction of 50% or more is required, and it should be possible to reduce the ratio by improving the system stabilization technology.

2.5. Technology scenarios to evaluate zero-carbon power generation systems

The power demand, renewable energy technology, and system stabilization technology are set as in the following. CO_2 emissions were evaluated for power systems under the constraint of 70% to 100% reduction toward zero-carbon power systems. Although energy conservation is progressing, it is expected that future electricity demand will increase. For this reason, we evaluated the power generation system assuming electricity demand ranging from 700 to 1400 TWh/y (the current electricity demand in Japan is about 1000 TWh/y). There are two cases of nuclear power capacity considered which can produce zero or 200 TWh annually. As a new technology that contributes to system stability, two cases of introducing hot dry rock (HDR) geothermal power generation [12] with annual power output of 100 or 200 TWh were also evaluated. The additional cost of the transmission grid was calculated based on the cost of upgrading the inter-regional transmission line at 150 Yen/kW/km. In this paper, we evaluated two cases of inertia fraction: one at the 50% level currently required, and a second with an inertia fraction of 25%, assuming technology improvements to stabilize grid systems.

3. Results and Discussion

First, we show the impact of power consumption and technology scenarios. Fig. 1 shows the maximum potential for CO_2 emission reduction versus annual electric power demand. By enhancing the current grid, in the case of the electricity demand of 1000 TWh, the CO_2 emission reduction is 83% (case a). In the case of the enhanced current grid, a 90% reduction in CO_2 emission is achievable (case c). Zero emissions can be achieved in the case of a power demand of 1000 TWh with the inertia fraction lowered from 50% to 25%(case d,f). On the other hand, at 1200 TWh or more of electricity demand, CO_2 emissions of the power supply system can only be reduced by 98% even in the HDR 100 TWh introduction case with an inertial force ratio of 25% (case f). The results show that, in order to achieve a zero-carbon power system,

we need technological developments that contribute to grid reinforcement and grid stabilization in addition to the technological development of renewable energy. Furthermore, it is clear that it becomes difficult to achieve zero emissions as the demand for electricity increases. The development of renewable energy technologies that contribute to system stability such as hot rock geothermal energy becomes important.
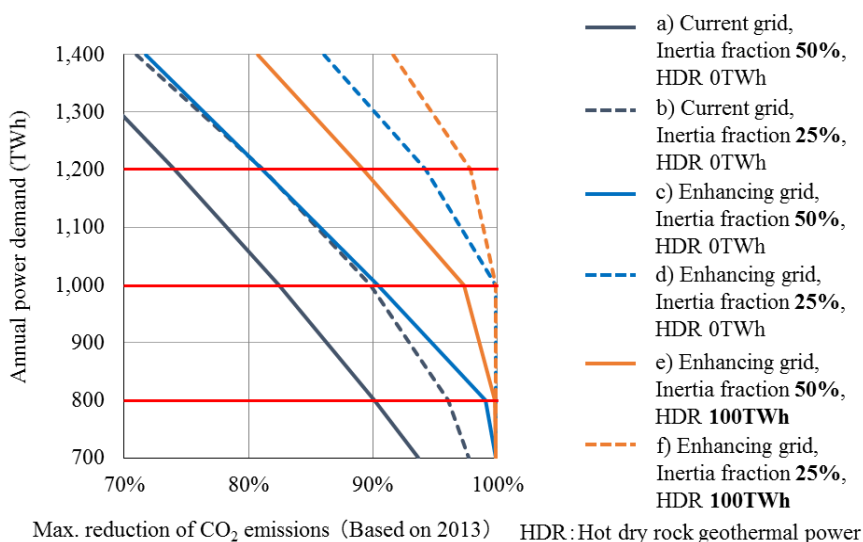

Fig. 1. Relationship between CO_2 reduction potential and power demand, highlighting the effect of the inertial force power fraction on the amount of CO_2 reduction

Second, we show the results of power cost modeling, for cases of electricity demand from 800 TWh to 1200 TWh, which can achieve zero emissions in the year 2050 (Table1). An 80% reduction of CO_2 emissions originating from power generation can be realized at almost the same cost as current power generation systems (Case 1). Achievement of zero emissions can be realized when the inertial force fraction is 25% (Cases 2 To 5). For the case of zero nuclear power and zero HDR geothermal power, the power cost is 14.3 and 16.5 yen / kWh at an electricity demand of 800 TWh / y (Case 2) and 1000 TWh / y (Case 4), respectively, while the current power cost is 12.9 yen/kWh.

As for the installed capacity of a photovoltaic power generation system, the potential of the possible installation area is insufficient at the existing conversion efficiency, so it is necessary to develop the technology aiming at 30% of the conversion efficiency. In addition, the required amount of storage batteries required for daily operation exceeds 800 GWh. Furthermore, in order to introduce a wind power generation system on a large scale for a zero-carbon power supply system, it is necessary to increase the electricity power transmission lines from Hokkaido and Kyushu which are far from the central area where the demand is large. Because of such large-scale power transmission issues, the capacity of the transmission line will need to be more than 10 times the existing capacity.

Furthermore, when 100 TWh/y of HDR geothermal power generation is introduced into the system, the power generation cost becomes 11.1 yen / kWh at 1000TWh of electricity demand (Case 3). However, electricity demand of 1200 TWh can only be achieved with a CO_2 reduction of 98% (Case 6). The introduction of 200 TWh of geothermal energy (Case 5) makes it possible to lower the cost of power generation to the current level or less.

Table 1. Power Cost of each case to achieve zero CO_2 emission

Case	1	2	3	4	5	6	7
Power demand	100	800	1000	1000	1200	1200	1200
Inertia fraction	50%	25%	25%	25%	25%	25%	25%
CO_2 reduction rate	80%	100%	100%	100%	100%	98%	90%
HDR introducing (TWh/y)	0	0	100	0	200	100	0
Generation Power (TWh/y)							
Nuclear power	0	0	0	0	0	0	0
Hydro power	130	130	130	130	130	130	130
LNG	317	0	0	0	0	32	159
PV	524	595	555	692	592	673	672
Wind power	211	402	344	559	509	537	441
Geothermal	12	12	12	12	12	12	12
Geothermal (HDR)	0	0	100	0	200	100	0
Biomass	31	22	31	29	31	30	30
Total	1,225	1,160	1,172	1,422	1,465	1,514	1,443
H2 generation (TWh/y)	51	67	9	106	24	43	29
Battery output (TWh/y)	227	252	294	242	156	297	308
Battery capacity (GWh)	801	821	983	809	643	920	1,013
Gene. Cost (Yen/kWh)[*]	11.7	14.3	11.1	16.5	12.1	12.9	11.7

* 10 Yen/kWh = 80 €/MWh

4. Conclusion

In this paper, we evaluated the technologies required for a zero-carbon power system after 2050 using a multi-region power generation model that accounts for system stability. We estimated future power generation costs using the technology scenarios developed by LCS under the constraints of reduced CO_2 emissions. The following issues were clarified for the requirements to establish a zero-carbon power system.

1) Large-scale introduction of renewable energy, in particular, developing a conversion efficiency of 30% of solar power generation to reduce plant area.
2) Installed capacity of storage batteries on a scale of 500 to 1000 GWh in order to alleviate short- and medium-term fluctuations and to integrate daily operations.
3) Reinforcement of the capacity of electricity grid system by at least 10 times the current level in order to use renewable energy from Hokkaido and Kyushu.
4) The inertial force constraint has the greatest influence on power generation cost. Set the fraction of the electricity supply provided by inertial generators to 25%, which is half of the current situation.
5) Reduction of power demand is effective. On the other hand, when the demand for electricity increases, the introduction of a stable power source of 100 to 200 TWh, such as HDR geothermal power generation is indispensable.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Toshihiro Inoue and Koichi Yamada conducted the research, performed the simulation, and wrote the paper; all authors had approved the final version.

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