Management of Surplus Electricity to Decarbonize Energy Systems in Japan

Yasuaki Kawakami*　Ryoichi Komiyama**　Yasumasa Fujii***

This paper presents roles of technologies which manage surplus electricity derived from a massive deployment of variable renewables (VRE) for energy system decarbonization in Japan. A bottom-up energy technology model which covers a whole energy system and incorporates a high-temporal-resolution power sector is developed and utilized. The model is formulated as a large-scale linear programming model with 11 million endogenous variables and 25 million constraints. Simulation results reveals that massive decarbonization results in the occurrence of huge amount of surplus electricity and requires installation of surplus electricity management technologies. Stored batteries, charging of electric vehicles and heat conversion as well as suppression of VRE power output would play substantial roles to manage the surplus electricity. A degree of utilization of electrolyzer depends on its cost and carbon constraints although the installed capacity is limited compared with other management technologies at any case assumed in this study.

Keywords : Variable renewables, Surplus electricity management, Energy system decarbonization, Linear programming

1. Introduction

Amidst the growing momentum for decarbonization initiatives around the world, in order to realize the decarbonization of energy systems in Japan, it is vital to achieve decarbonization of the power sector, which is the main source of carbon dioxide (CO_2) emissions. The 5th Strategic Energy Plan sets out the goal of making renewable energy the main source of power by 2050. In the case where variable renewable energy (VRE) such as solar PV and wind is massively deployed in the power sector, surplus electricity is expected to be generated from the perspective of balancing power demand and supply. Some ways of managing this surplus electricity include measures by the power sector, such as suppressing output or using power storage technology (pumped hydro, large-scale batteries), and non-electrical conversion, such as water electrolysis hydrogen production, methanation, and heat conversion. The latter is expected to contribute to the effective use of electricity, in addition to the decarbonization of the non-power sectors.

A bottom-up optimization model that analyzes the overall energy system may be useful for analyzing technologies that aim to realize decarbonization, but as conventional models provide an extremely concise expression of the power sector, they may not necessarily be able to offer a detailed analysis of the issues faced by the power sector, including the generation of surplus electricity. On the other hand, although models that are specific to the power sector are able to provide a detailed analysis of such issues, they pose problems when it comes to analysis on the utilization of surplus electricity in non-power sectors and the consideration of substitutes between the power and non-power sectors. This study develops a new techno-economic optimization model to analyze the role that technologies used to manage surplus electricity can play in the decarbonization of energy systems in Japan, from the perspectives of the capacity of the technology that is installed, and the operation of the technology.

2. Methodology

2.1 Multi-regional dynamic model

Using the bottom-up energy system optimization model developed by the authors, an analysis is carried out for the optimal configuration of energy technology to realize low carbonization in the future. This is a linear programming model, modeled after the MARKAL/TIMES[1)] model generator that was developed based on IEA's technology evaluation program (Energy Technology Systems Analysis Program, or ETSAP). The subject of analysis is the overall energy system (Figure 1). The objective function is the discounted total cost of the system. Its greatest characteristic is the fine temporal resolution of 60

* Yasuaki Kawakami, PhD, Economist
Oil Group, Fossil Energies & International Cooperation Unit
The Institute of Energy Economics, Japan
** Ryoichi Komiyama, PhD, Associate Professor
Energy System Resilience, Resilience Engineering Research Center
The University of Tokyo
*** Yasumasa Fujii, PhD, Professor
Energy System Resilience, Resilience Engineering Research Center
The University of Tokyo

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minutes (8760 time segments/year) for the power sector and energy storage, and its ability to consider explicitly the diurnal variations and seasonal variations of VRE output. Compared to the limitations of conventional energy system optimization models—the yearly time segments are limited to mostly 4 – 48[2], it is able to conduct a detailed analysis of the power sector, including the consideration of the load following capability of various power generation technologies and constraints over minimum output of thermal generation. For details of the model, see the reference[3]. This study expands on the model set out in the same reference material, setting the period of analysis to 2050, while consolidating the regional categories to four categories (Hokkaido, Tohoku, Kanto, and West Japan) in order to reduce computational cost.

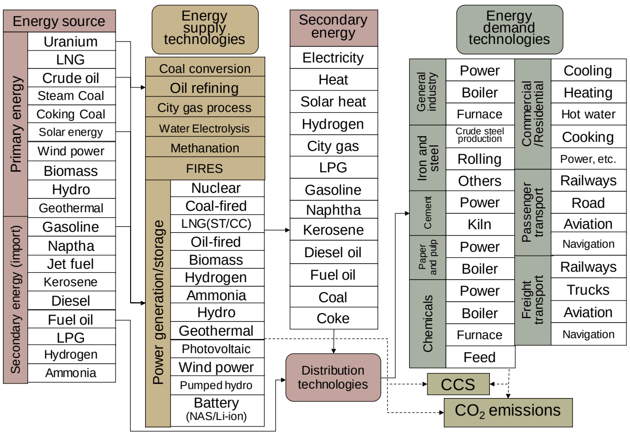

Figure 1 Reference energy system

2.2 Surplus electricity management technology

The surplus electricity management technology that is taken into consideration are the suppression of VRE power output, pumped hydro, large-scale storage batteries (NAS batteries and Li-ion batteries), electric vehicle (EV) charging, water electrolysis hydrogen production, methanation, and heat conversion (FIRES). It is assumed that generated power through VRE can be suppressed within a range that does not exceed that output. The charging time for EV (in this paper, this includes plug-in hybrid vehicles) is from evening to early morning, and the charging pattern is determined endogenously. It is important to note that the charging pattern is determined from the perspective of minimizing total cost, or in other words, from the perspective of supply-side optimization. Hydrogen and heat storage, like the power sector, are expressed in 60-minute intervals, and the cost of storage is taken into consideration. On the other hand, hydrogen and heat demand are assumed to be constant throughout the year. FIRES is a technology that converts surplus electricity to heat through electric heat resistance, and which stores heat in a massive heat storage tank. This paper assumes that heat is used once again for power generation, or is used to fulfill heat demand in the industrial sector.

3. Premise of calculations

3.1 Prerequisites

The parameters for power generation technology and electricity storage technology are set based on reference material [4] and other sources (Table 1, Table 2). The items that are shown as a range in the table are expected to be mastered or achieve technological development by 2050, and the settings vary depending on the period.

Table 1 **Assumptions for power generation technology**

	Nuclear	Coal	LNGCC	LNG	Oil	Hydrogen	Ammonia
Construction cost [Thousand yen/kW]	370	272	164	120	200	164	164
Fixed cost ratio (against construction cost)[%]	5.2	4.0	3.0	3.0	3.2	3.0	3.0
Efficiency (Sending end, LHV)[%]	-	39~44	54~61	42	38~40	54~61	54~61
Maximum capacity factor [%]	80	80	80	80	80	80	80
Upper limit of output adjustment rate (increase) [%/hour]	0	31	82	82	100	82	82
Upper limit of output adjustment rate (decrease) [%/hour]	0	58	75	75	100	75	75
Number of years of operation [Years]	40	40	40	40	40	40	40
DSS operation ratio [%]	0	0	50	30	70	0.5	0.5
Minimum output ratio [%]	30	30	30	30	30	30	30
	Hydro	**Biomass**	**Geothermal**	**Heat storage**	**Solar PV**	**Onshore wind**	**Offshore wind**
Construction cost [Thousand yen/kW]	640	398	790	120	294~152	284~227	591~506
Fixed cost ratio (against construction cost)[%]	1.4	6.8	4.2	3.0	1.4	2.1	3.8~3.1
Efficiency (Sending end, LHV)[%]	-	18	-	40	-	-	-
Maximum capacity factor [%]	53	80	70	80	-	-	-
Upper limit of output adjustment rate (increase) [%/hour]	5	31	5	82	-	-	-
Upper limit of output adjustment rate (decrease) [%/hour]	5	58	5	75	-	-	-
Minimum output ratio [%]	-	-	-	50	-	-	-
Number of years of operation [Years]	60	20	40	20	20	20	20

Table 2 Assumptions for electricity storage technology

	Pumped hydro	NAS batteries	Li-ion batteries
Construction cost [Thousand yen/kW]	190	35	40
Construction cost [Thousand yen/kWh]	10	40~20	150~15
Fixed cost ratio (against construction cost)[%]	1.0	1.0	1.0
Maximum capacity factor [%]	90	90	90
Cycle efficiency [%]	70	85	85
Self discharge rate [%/hour]	0.1	0.5	0.5
Maximum kWh/kW ratio	6	-	-
C rate	-	0.14C	2.0C
Cycle life [no. of times]	∞	4,500	6,000
Number of years of operation [Years]	60	15	8

For the output pattern for power generation through VRE (PV, onshore wind power), actual values estimated based on weather data is used into the future. For offshore wind power, the output pattern at representative points in each region are estimated using a web application [5], and used to represent each region. An upper limit is set for the VRE capacity by region, and the total upper limit values for Japan are as follows: for PV, 100GW for 2030 and 332GW for 2050, and for onshore wind power, 10GW and 100GW respectively. The changes in the residual existing thermal power generation facilities are set based on the assumption of 40 years of operation from the start of operation, taking reference from reference material [6] and other sources. For nuclear power, power plants that are in operation are assumed to be in operation for 60 years (installed capacity for 2050 is 21GW). Interconnection lines between regions are assumed not to be augmented in the future, with the exception of the lines Hokkaido-Tohoku, Tohoku-Kanto, and Kanto-West Japan, for which augmentation has already been decided on.

Surplus electricity management technology, excluding electricity storage technology, is established based on reference materials [7] and [8] (Table 3). The cost of EV charging facilities is assumed to be 310,000 yen/6kW[9].

Table 3 Assumptions for surplus electricity management technology

Electrolysis	Investment cost	180 - 100 million yen/(300Nm^3/h)
	Hydrogen production intensity (Electricity)	5~4.5 kWh/Nm^3-H_2
	Upper limit of utilization rate	90%
Electrolysis +Methanation	Investment cost	3~1.67 million yen/Nm^3-CH_4/h
	Methane production intensity (Electricity)	18.3 kWh/Nm^3-CH_4
	Methane production intensity (CO_2)	1.972 kg/Nm^3-CH_4
	Upper limit of utilization rate	90%
Hydrogen storage	Investment cost (kW)	70,000 yen/kW
	Investment cost (kWh)	1500 yen/kWh
	Cycle efficiency	90%
	Upper limit of utilization rate	90%
FIRES	Investment cost (charging-kW)	1000 yen/kW
	Investment cost (output-kW)	1000 yen/kW
	Investment cost (storage-kWh)	1500 yen/kWh
	Heat conversion efficiency	1
	Self discharge rate	1 %/h
	Upper limit of utilization rate	90%

Energy service demand until 2050 is calculated using an econometric method for total demand across Japan in the 36 sectors established. This is then allocated to each region using indicators such as energy consumption by region (actual values for 2015).

The upper limit for the amount of carbon-free hydrogen and ammonia that can be imported is assumed to be zero for the former, and 10 million tons in 2050 for the latter. Hydrogen can be manufactured in Japan through natural gas reforming or water electrolysis. CO_2 storage potential through CCS is assumed to be 100,000 tons in 2030 and 1 million tons in 2050.

3.2 Case setting

This paper sets assumptions for, and analyzes, multiple cases related to constraints in the reduction of energy-related CO_2, cost of water electrolysis equipment, and PV cost (Table 4). Two cases are set for CO_2 emissions volume: 50% reduction and 60% reduction by 2050 based on FY2013 levels. The upper limit of constraints for 2030 emissions is 927 million tons, which is the same level presented in the long-term energy demand and supply forecast by the METI. For PV and water electrolysis costs, the figures shown in Tables 1 and 3 are the standard case, but will be regarded as the low-order case if 2050 costs are lower. Specifically, water electrolysis cost for 2050 is 50 million yen/(300Nm^3/h) while PV cost is 100,000 yen/kW.

Table 4 Case setting

Case	CO_2 reduction rate	Water electrolysis cost	PV cost
C50	50%	Standard	Standard
C50/Electro	50%	Low	Standard
C50/Electro/PV	50%	Low	Low
C60	60%	Standard	Standard
C60/Electro	60%	Low	Standard
C60/Electro/PV	60%	Low	Low

4. Results and analysis

4.1 Power sector

If the constraints on CO_2 reduction become more stringent through to 2050, the fossil fuels used for power generation will increasingly shift from coal to natural gas (Figure 2). In the case where reduction rate is 50%, the power generation share for LNGCC in 2050 will reach 50% at the highest; however, if reduction rate were to rise further to 60%, fossil fuel share will fall to approximately 30%. On the other hand, the volume of VRE deployed will increase (Figure 3), and the amount of power generated will reach approximately 40%. In the low-order case for PV cost, the amount of PV deployed will increase significantly over the standard case, regardless of the rate of CO_2 reduction. In the case where CO_2 reduction rate is 60%, CO_2 emission intensity in the power sector for 2050 falls to about 110g-CO_2/kWh.

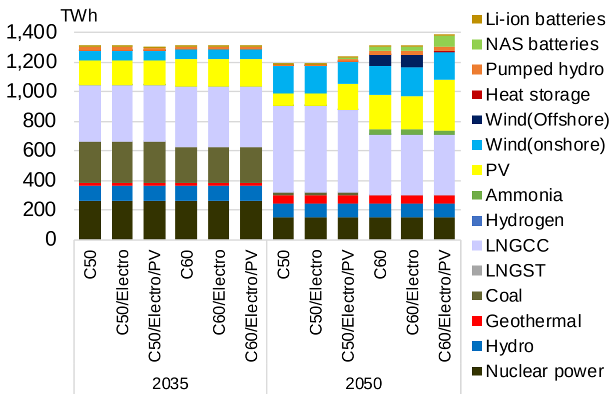

Figure 2 Configuration of power generation capacity

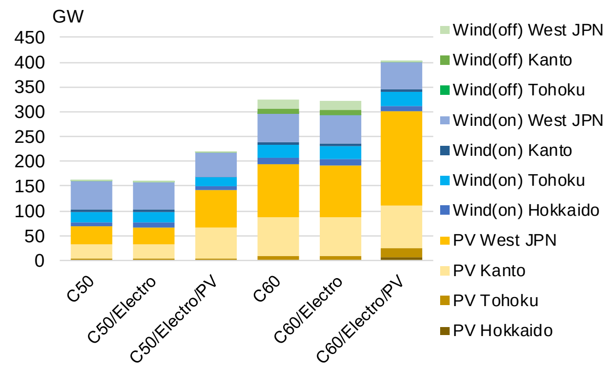

Figure 3 VRE generation installed capacity (2050)

Table 5 Installed capacity of major surplus electricity management technology in 2050

	Pump-storage	NAS batteries	Li-ion batteries	Water electrolysis	Methanation	FIRES
	GW	GW	GW	Thousand Nm^3-H_2/h	Thousand Nm^3-CH_4/h	GW
C50	25.6	0.4	0.3	47.1	10.6	31.6
C50/Electro	25.6	0.4	0.3	65.5	16.7	26.7
C50/Electro/PV	26.9	0.6	0.3	69.8	18.9	51.6
C60	27.6	23.6	0.8	56.9	15.0	82.1
C60/Electro	27.6	23.0	0.6	73.6	81.2	80.7
C60/Electro/PV	27.6	52.5	0.7	76.8	68.9	85.9

4.2 Surplus electricity management technology

The installed capacity for the major surplus electricity management technology in 2050 is shown in Table 5. To realize CO_2 emission reduction exceeding 50% by 2050, it would be rational to introduce storage batteries, water electrolysis, methanation, and FIREs as surplus electricity management technology. There has been no progress in the introduction of storage batteries in the 50% reduction case, for which the VRE generation deployment is limited. However, in the 60% reduction case, which sees a significant rise in the deployment of VRE, progress is seen mainly in the introduction of NAS batteries. For water electrolysis and methanation, while a certain installed capacity is introduced even in the C50 case, the quantity is approximately 3PJ/year and facility utilization rate is also low at about 10%, while the respective production volumes are less than 1% of the demand volume (hydrogen and city gas). We could say that the introduction of these two technologies has been limited due to the high costs incurred in electrolysis and storage. Even so, generally, the greater the increase in CO_2 reduction rate, and the lower the electrolysis cost, the greater the growth in the introduction of these technologies. However, in the case of methanation, as CO_2 is generated through the combustion of methane, CO_2 constraints are severe, and the degree of introduction of the technology falls in the case where zero-carbon power generation costs are cheap, such as PV. In the overall adjustment of power demand and supply, the management of surplus electricity through means such as stationary storage batteries, EV charging, heat storage through FIRES and heat utilization in final demand, and power transmission to other regions make up the larger part of measures taken. Of course, it must be said that in either case, the suppression of VRE power output arises, and in the case of C60/electrolysis/PV, the amount of output suppressed reaches 18.2TWh for PV (suppression rate of 5.1%), and 7.5TWh for onshore wind power (suppression rate of 3.8%). As this leads to excess facilities for the management technology (decline in utilization rates), we could say that it would not be rational to fully absorb surplus electricity.

4.3 Operation of surplus electricity management technology

Power demand and supply operation for April to May 2050 in the Tohoku region, in the C60/electrolysis/PV case where power generation through VRE is deployed the most, is shown in Figure 4.

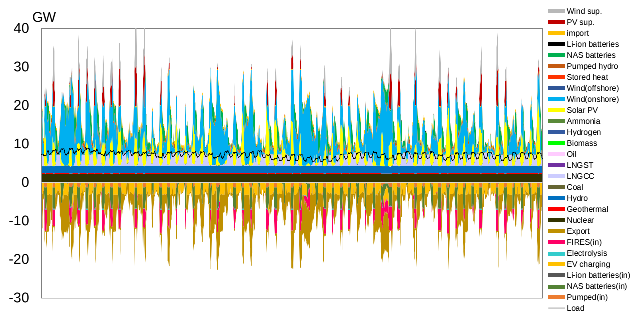

Figure 4 Power demand and supply operation for April to May (2050 Tohoku region, C60/electrolysis/PV case)

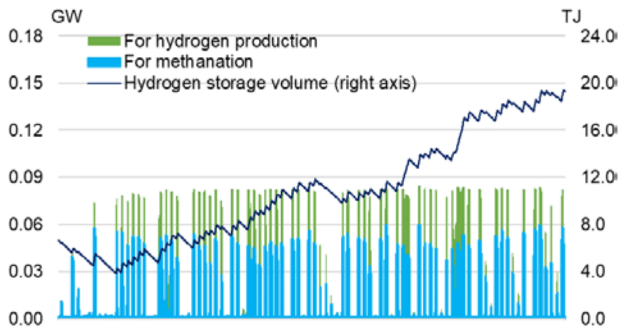

Figure 5 Operation of water electrolysis equipment, and volume of hydrogen storage, for April to May (2050 Tohoku region, C60/electrolysis/PV case)

With nuclear power and general hydropower operating at a constant output, the introduction of PV and onshore wind power that significantly exceed the scale of power demand makes the adjustment of power demand and supply through the flexible operation of LNGCC or the use of pumped-storage power generation difficult. This results in the generation of a large amount of surplus electricity. As explained earlier, a large part of surplus electricity is absorbed through stationary storage batteries (NAS batteries), EV charging, and heat storage, or is managed through power transmission to other regions or output suppression. In the same case, 66% of the vehicles in 2050 (percentage based on transport volume) will be plug-in hybrid cars.

Figure 5 shows the operation of water electrolysis equipment for the same period and the changes in hydrogen storage volume. Corresponding to the generation of surplus electricity, a maximum of about 0.1GW of electricity is consumed by the water electrolysis equipment used in hydrogen production and methanation. Through May, as VRE output increases, the operation of electrolysis equipment increases, and hydrogen storage volume also increases.

It is important to note that this study does not take into consideration the uncertainty of VRE output and constraints to ensure the LFC (load frequency control) ability.

5. Conclusion

Using a bottom-up energy system optimization model that can take into consideration power sector and energy storage at a high temporal resolution, we analyzed the role of surplus electricity management technology toward low carbonization in the future. To realize significant low carbonization of 60% reduction in CO_2 emissions by 2050, it is necessary to achieve low carbonization in the power sector through the massive deployment of VRE power generation. The surplus electricity that is generated through this is mainly managed through storage batteries, EV charging, heat conversion, and output suppression. For the production of hydrogen through water electrolysis and methanation, a certain installed capacity is introduced; while the degree of introduction of the technologies increases through tighter constraints on CO_2 reduction and reduction in water electrolysis cost, they are more limited in comparison with other management technologies.

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