A Study on the Utilization of Ammonia as Energy in Japan

Zheng LU*, Yasuaki KAWAKAMI* and Harumi HIRAI*

* The Institute of Energy Economics, Japan

1-13-1 Kachidoki, Chuo-ku, Tokyo 104-0054

In this study, using an optimization model, we estimated the needed amount of imported ammonia as energy for Japan to achieve the 80% reduction of energy-related CO_2 emissions by 2050 from 2013 level, based on the outlook for energy service demand. The results show that, when constraint of CO_2 emissions is extremely severe, the power sector should approach almost zero emissions in 2050. In Japan, if the storage capacity for CO_2 is limited, and ammonia remains less expensive than hydrogen, about 186 million tons of ammonia is needed for power generation in 2050, and its share in power generation reaches 51%. Meanwhile, the share of electricity in the final demand rises substantially, and the shift from fossil fuel to hydrogen is much limited. However, in such a case, energy supply is still relying on import, and excess dependence on electricity may reduce the flexibility in final demand. It is preferable to pursue the "best balance" in ammonia/hydrogen, domestic CCS and high efficient technologies in final use with competitive cost as well.

Keywords: Ammonia, Hydrogen, CO_2 emission reduction

1. Introduction

Aiming to use hydrogen for energy supply, Japan has been making progress in the development of fuel cells (FCs) and fuel cell vehicles (FCVs), which are now entering practical use. Progress has also been made in the R&D of massive hydrogen-fired power generation, which is expected to effectively help achieve strict CO_2 emissions reduction targets when applied to massive power generation. However, huge amounts of hydrogen will be necessary, requiring the construction of an entire supply chain including production (electrolysis), storage and transportation.

Ammonia, on the other hand, can be produced using the Haber-Bosch process from hydrogen and the nitrogen separated from air. Ammonia is used as a chemical fertilizer and chemical raw material and is traded worldwide in global markets. Unlike hydrogen, ammonia liquefies easily under light pressurization or cooling, enabling it to be handled relatively easily. While the use of ammonia would require the construction and deployment of new facilities, it would not require building supply chain facilities which are technologically new. Like hydrogen, ammonia does not generate CO_2 during combustion, and so, along with hydrogen, has been attracting attention as a new energy carrier. In particular, when using ammonia in massive power generation, once ammonia turbine technologies and mixed-combustion technologies for existing thermal power plants are established, this could be achieved merely by expanding existing facilities. In terms of economic efficiency, widespread deployment of ammonia in the power generation sector could begin at a relatively early stage.

There are two ways for producing hydrogen: the electrolysis of water and the steam reforming of hydrocarbons such as natural gas. Like these two ways for producing hydrogen as raw material, there are two ways for producing ammonia. The usual method for commercial production is based on the extraction of hydrogen from hydrocarbons such as natural gas. Ammonia examined in this study is assumed to be produced outside Japan by synthesis from hydrogen, which is produced by steam reforming from natural gas, and it is assumed that most of the CO_2 generated in the production process is captured and sequestered by using CO_2-EOR (third recovery of crude oil).

If the production and import of such CO_2-free ammonia is realized, how would it affect the energy supply structure of Japan? This is the question addressed in this study. Specifically, assuming that Japan is to achieve by 2050 an 80% reduction in energy-related CO_2 emissions from the 2013 level, we predicted the demand for energy services up to 2050 using a macro-econometric model. Then, after making assumptions on the prices and costs of imported hydrogen, ammonia, domestic CCS and so on, we estimated the scale of deployment of ammonia, etc., using an optimization model (MARKAL).

2. Analysis Method

This analysis considered the period from 2030 to 2050.

The analysis flow is illustrated in Figure 1. After predicting the demand for energy services using the macro-econometric model, we defined the constraints and assumptions necessary in the optimization model such as assumptions on prices and CO_2 emissions and estimated the scale of ammonia deployment using the optimization model (MARKAL).

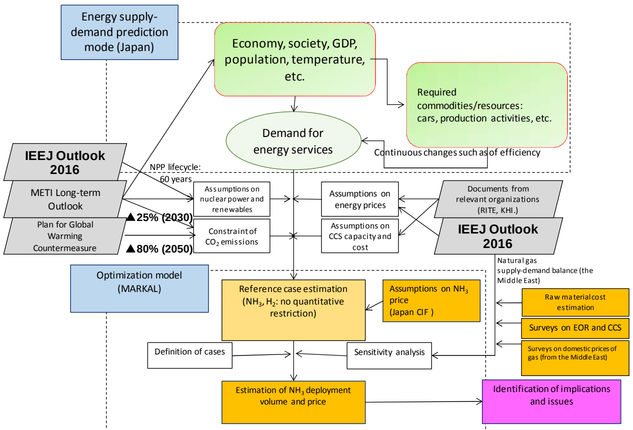

Figure 1: Analysis flow (overall)

3. Assumptions Used in Analysis and Cases Defined

3.1 Macro Economy

Table 1 lists major assumptions of the macro-econometric model used for estimating the demand for energy services. The population and number of households are assumed on the basis of mid-level estimates of births and deaths in "Estimated Future Population of Japan, estimated in January 2012" from the National Institute of Population and Social Security Research. The gross domestic product (GDP) up to 2030 is assumed in line with the Government's Long-term Energy Supply and Demand Outlook. The GDP after 2030 was estimated using econometric methods, predictions by international organizations, etc.

Table 1: Major assumptions for the macro-econometric model

		2013	2020	2030	2040	2050
Population	million persons	127	124	117	107	97
Number of households	million households	56	56.5	54.7	51.2	47.2
Real GDP	trillion 2005 yen	531	607	711	780	827
Crude steel production	million tons	112	113	115	112	106
Total floor space for business use	million m^2	1,845	1,910	1,993	2,035	1,995

3.2 Energy Prices

Table 2 lists assumptions on the prices of crude oil and natural gas in global markets. The figures are from the IEEJ's Asia/World Energy Outlook 2016 (hereinafter "IEEJ's Outlook").

Table 2: Assumptions on international energy prices

			2015	2020	2030	2050
Crude oil	USD/bbl	Real	52	75	100	130
		Nominal	52	83	135	260
Natural gas	Japan	Real	536	554	663	751
	USD/t	Nominal	536	611	892	1,501
	Japan	Real	10.4	10.7	12.8	14.5
	USD/MBtu	Nominal	10.4	11.8	17.2	29.0
	Europe	Real	6.5	8.5	9.8	12.2
	USD/MBtu	Nominal	6.5	9.4	13.2	24.4
	USA	Real	2.6	4.5	5.6	6.9
	USD/MBtu	Nominal	2.6	5.0	7.5	13.8
Steam coal	USD/t	Real	80	89	106	138
		Nominal	80	98	142	275

Table 3 : Assumptions on hydrogen and ammonia CIF prices

	Unit	2030	2040	2050
Hydrogen	(2015\$/Nm^3)	0.47	0.38	0.30
Ammonia	(2015\$/ton)	419	441	459
Hydrogen	(2015\$/10^6 Btu)	38.4	31.7	25.1
Ammonia	(2015\$/10^6 Btu)	20.0	21.1	22.0
LNG	(2015\$/10^6 Btu)	12.8	14.1	14.5

Based on information collected in interviews with stakeholders, we calculated the ammonia production cost (plus freight) in 2030. As the price of natural gas as the raw material for ammonia production, we employed the price of natural gas in the United States. Since ammonia production technologies, particularly those based on the Haber-Bosch method, are mature technologies, we assumed that the raw material cost (natural gas price) in the period after 2030 is the only component of production cost that may change. As the imported hydrogen supply cost (including production cost and infrastructure cost) is likely to change thanks to future technological development and cost reductions, we determined hydrogen prices in the period from 2030 to 2050.

3.3 Scales of Energy Utilization Technology Deployment and Major Indicators

In the optimization analysis, the scales of deployment of nuclear power and renewables were regarded as exogenous. The installed capacity of nuclear power generation was estimated based on the rule “no new reactor installation plus 60-year operation of existing reactors” set after the Great East Japan Earthquake. The total capacity of nuclear power generation is expected to remain above 40 GW until 2035 and then start decreasing, reaching about 20 GW in 2050. The capacity of renewables-based power generation was estimated as shown in Figure 2 based on the Government's Long-term Outlook (for years up to 2030) and the IEEJ's Outlook.

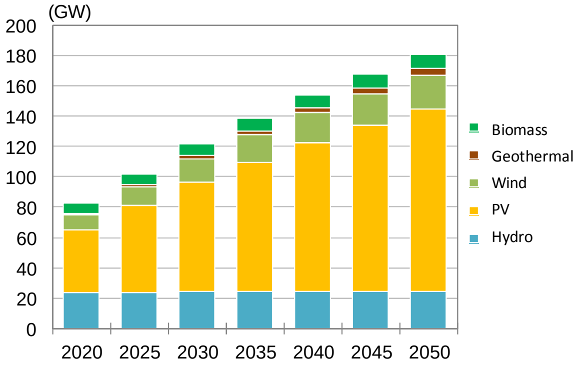

Figure 2: Assumptions on the installed capacity of renewables-based power generation

The generation costs for different type of power generation were assumed on the basis of estimates provided by the Power Generation Cost Verification Working Group of the Advisory Committee for Natural Resources and Energy. The cost and efficiency of hydrogen/ammonia-fired power generation were estimated on the basis of indicators of LNG-fired power generation. The building of new power generation facilities for the mixed combustion of ammonia with coal or natural gas (20% mixed combustion on calorie basis) are also considered in this analysis. The cost and generation efficiency of ammonia mixed power generations were estimated in consideration of changes from solely coal-fired and solely LNG-fired power plants.

Table 4: Assumption on the costs and efficiencies of LNG-fired, hydrogen-fired and ammonia-fired power generation

Cost of investment	
LNG-fired power	120,000 yen/kW
Hydrogen-fired Power	120,000 yen/kW
Solely ammonia-fired Power	120,000 yen/kW
Generation efficiency (sending end)	
LNG-fired power	49% HHV
Hydrogen-fired Power	49% HHV
Solely ammonia-fired Power	49% HHV

3.4 Other Assumptions

Regarding energy-related CO_2 emissions, we assumed that a reduction of approximately 25% from the 2013 level must be achieved by 2030 as stated in the Government's Long-term Outlook, and 80% by 2050.

In addition, it was assumed that the thermal power generation sector and some industrial sectors will employ CCS to reduce CO_2 emissions. Referring to the estimation by the Research Institute of Innovative Technology for the Earth (RITE) in 2007, it is assumed that the cost of CCS is about 100 US$/t-$CO_2$, and the maximum annual sequestration capacity is 62 million tons in 2040 and 115 million tons in 2050, and the maximum cumulative sequestration capacity up to 2050 is about 1 billion tons.

3.5 Cases for the Optimization Analysis

In the optimization analysis, we defined a "reference case" without imposing any limit on the amounts of ammonia and hydrogen, in order to determine the maximum potential for the deployment of ammonia. In addition, considering the risk of procuring resources from abroad, we prepared a "restricted power generation case" to impose limits on the shares of ammonia and hydrogen in the generation mix to an extent that would not prevent achieving an 80% reduction of CO_2 emissions by 2050.

Table 5: Preparation of two cases for the optimization analysis

	Reference case (maximum deployment of ammonia)	Restricted power generation case (limit on the share of hydrogen and ammonia in power generation)
Restriction on CO2 emissions	80% reduction by 2050 (from the 2013 level)	Same as left.
Ammonia	Used for power generation (without limit)	Same as left, except that the su share of hydrogen and ammonia in the total power generation should not exceed 25%.
Hydrogen	Used for power generation and final consumption (without limit)	
CCS	Employed in power generation and some industrial sectors (up to the capacity limit based on mid-level estimate)	Same as left.

4. Analysis Results

4.1 Outlook on the Demand for Energy Services

Figure 3 shows a part of the demand for energy services estimated on the basis of the assumptions discussed in Section 3.1. In the industry sector, the activities of raw material production industries are expected to decrease overall due to factors such as changes in the industrial structure characterized by a transition to tertiary industries, excepting the sectors such as steel manufacturing where exports are forecasted to increase thanks to global economic growth, and the chemical industry where the production of high added-value products (functional chemical products) is expected to increase. The demand for energy services is expected to show a similar trend. In the transportation sector, the demand for energy services associated with passenger vehicles (passenger-kilometers) is expected to decrease as the number of cars owned will fall as a result of the decreasing population and aging society while the energy service demand for cargo vehicles is expected to increase because of an increase in materials flow resulting from GDP growth.

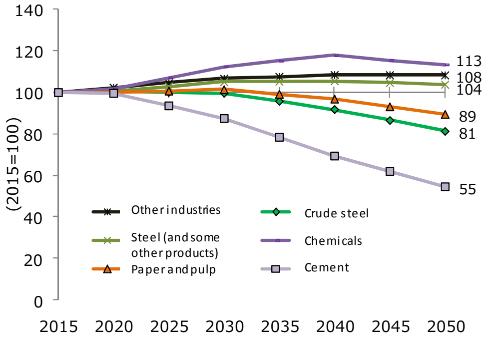

Figure 3: Example of estimated demand for energy services (in industrial sector)

4.2 Results of Optimization Analysis

In the reference case, the use of zero-emission power sources such as nuclear power and renewables reach the maximum limitation, the stricter control of CO_2 emissions, will rapidly reduce the reliance on thermal power generation while ammonia-fired power generation will increase. Although attempts will be made to combine thermal power generation with CCS, the share of electricity from such CCS-combined plants will be limited. By 2050, the deadline for achieving an 80% reduction of CO_2 emissions, the power generation sector is expected to nearly achieve zero emissions, and the share of ammonia-generated power is expected to reach 51% (see Table 6). Meanwhile in the breakdown of final energy demand, the demand for hydrogen is expected to remain almost zero while the share of electricity is expected to reach 46% in 2050. This suggests that promoting electrification (considering that the transition from fossil fuel to low-carbon fuel in the industry sector and the transportation sector is costly) and employing zero-emission power sources constitute the most efficient and least costly approach.

In the restricted power generation case, on the other hand, in the period after 2040, the ammonia-fired power generation which reach the imposed limit (25% share in the generation mix), will be followed by the CCS-combined thermal power generation as much as possible until no more capacity remains (see Table 7). Regarding the final energy demand, a huge volume of hydrogen will be used not only in the area of FCVs and FCs, but also in areas such as boilers and heating furnaces, for which hydrogen can hardly increase in the reference case because of its relatively high cost, thus limiting electrification to a certain extent.

A comparison of the two cases suggests that, in selecting generation options in view of reducing CO_2 emissions, the first choice will be to use as much nuclear power and renewables as possible, after which the deployment of ammonia-fired power generation and CCS-combined thermal power generation will be considered. Ammonia-fired power generation is a zero-emission option while CCS is a low-emission option (the CO_2 recovery rate in CCS is around 90%, remains will be released to the atmosphere). Therefore, if very strict CO_2 emission controls are implemented, ammonia-fired power generation is more likely to be chosen than CCS. However, if there are constraints that prevent the unlimited use of solely ammonia-fired power generation and hydrogen-fired power generation, CCS will be used more to compensate for them, and the share of hydrogen in the final energy demand will increase.

Table 6: Major results of analysis of the reference case

		2030	2035	2040	2045	2050
Generation mix (%)	Nuclear	20	25	23	22	14
	Renewables (including hydro)	24	27	31	34	33
	Thermal without CCS	55	47	35	17	1
	Thermal with CCS	0	0	0	2	2
	Hydro	0	0	0	0	0
	Ammonia mixed combustion	0	0	0	0	0
	Solely ammonia-fueled	0	0	10	24	51
	Others	0	0	0	0	0
Hydrogen deployment (Unit: 0.1 billion Nm3)	Total	0	0	0	0	2
	Industry	0	0	0	0	0
	Commercial/residential	0	0	0	0	0
	Transportation	0	0	0	0	2
	Power generation	0	0	0	0	0
Ammonia deployment (million tons)	Power generation	0	0	35	81	186
CO2 sequestration by CCS (million tons)		5	19	62	67	63

Table 7: Major results of analysis of the restricted power generation case

		2030	2035	2040	2045	2050
Generation mix (%)	Nuclear	20	25	23	22	15
	Renewables (including hydro)	24	27	31	34	36
	Thermal without CCS	53	44	32	14	1
	Thermal with CCS	0	0	1	11	18
	Hydro	0	0	0	0	0
	Ammonia mixed combustion	2	3	4	3	2
	Solely ammonia-fueled	0	0	9	16	25
	Others	0	0	0	0	4
Hydrogen deployment (Unit: 0.1 billion Nm3)	Total	0	0	0	1	708
	Industry	0	0	0	0	342
	Commercial/residential	0	0	0	0	277
	Transportation	0	0	0	1	88
	Power generation	0	0	0	0	0
Ammonia deployment (million tons)	Power generation	1	2	35	54	85
CO2 sequestration by CCS (million tons)		5	19	62	96	115

4.3 Sensitivity Analysis for the Amount of Ammonia Deployed

Next, we analyzed how changes to various assumptions in the reference case may affect the scales of deployment of ammonia, hydrogen and CCS.

1) If the constraint of CO_2 emissions reduction ratio is lowered, the deployment of ammonia drops sharply. Supposing that the reduction ratio for achievement by 2050 is lowered to 70% or 60%, then the share of ammonia-fired power generation in the generation mix is expected to drop to 20% or 8%, respectively. Widespread deployment of ammonia-fired power generation beginning from 2040 in the reference case, will be put off (see Figure 4). In the final energy demand, costly switching from conventional fuel to hydrogen slows down while CCS-combined thermal power generation is expected to be implemented until the storage limit for captured CO_2 is reached. This suggests that CCS-combined thermal power generation will be found to be relatively economically advantageous as long as the CO_2 emission reduction requirement is relatively low.

2) The results of sensitivity analysis on the CCS capacity limit indicated that, if the storage capacity for captured CO_2 is zero, the contribution of solely ammonia-fired power generation will be even greater, and the share of ammonia-mixed combustion plants in the generation mix is expected to be around 5%. Under this scenario, the inability to implement CCS in industries like steel and cement will have to be compensated by progress in the deployment of hydrogen in the transportation sector (see Figure 5). Conversely, if there is no limit to the storage capacity for captured CO_2, the deployment of ammonia will be less while the quantity of CO_2 sequestered by CCS will increase. However, since CCS will not sufficiently offset emissions from the power generation sector, additional reduction will have to be achieved by increasing the use of FCVs in the transportation sector. Supposing that the storage capacity for captured CO_2 varies between zero and infinity, then the resulting variation in the scale of deployment of ammonia will be greater in 2040 than in 2050. Around 2040, the CO_2 emission reduction requirement is still not too severe; hence, the scale of CCS deployment impacts the scale of ammonia deployment significantly, while in 2050, if an 80% reduction is required, the impact will be less.

3) In the reference case, we assumed cost-based pricing of ammonia. Supposing a higher ammonia price of 569 $/t with profits added, then the predicted amount of ammonia deployment in 2050 decreases from 186 to 135 million tons (see Figure 6). The quantity of CO_2 sequestered by CCS is expected to increase up to the storage capacity limit, and in the final energy demand FCVs will increase.

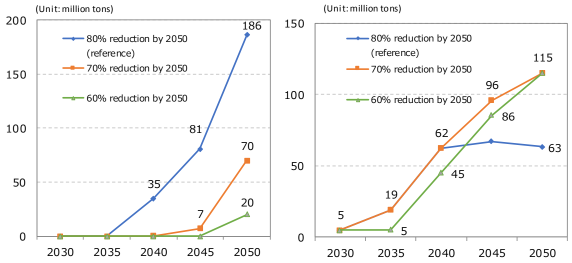

Figure 4: Scales of deployment of ammonia (left) and CCS (right) by CO_2 emissions reduction requirement

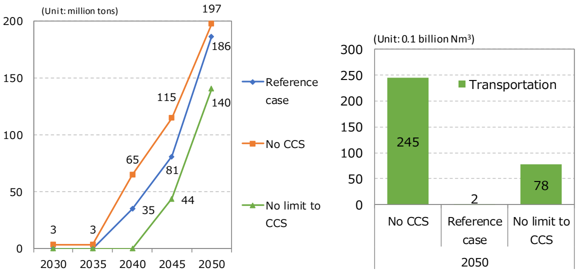

Figure 5: Scales of deployment of ammonia (left) and hydrogen (right) by the limitation of CCS capacity

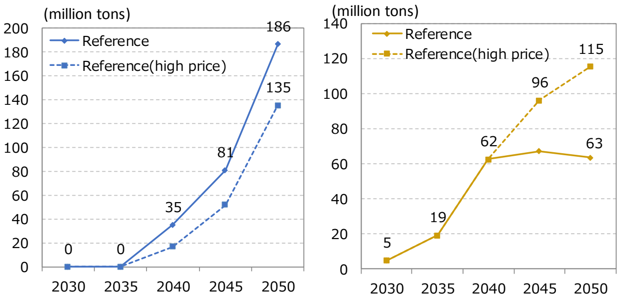

Figure 6: Scales of deployment of ammonia (left) and CCS (right) by ammonia CIF price

5. Conclusion

Our study has shown that, given very strict controls on CO_2 emissions targeting a reduction of 80% (from the 2013 level) by 2050, the power generation sector will be obliged to achieve nearly zero emissions. Supposing that the domestic capacity for storing CO_2 sequestered by CCS is several hundred million tons and that ammonia remains less costly than hydrogen as a power source, then it is predicted that the annual quantity of ammonia deployed for power generation will reach about 186 million tons and a 51% share in the power generation by 2050. If the implementation of CCS is delayed, power generation by ammonia-mixed combustion can serve as a mid-term option for reducing CO_2 emissions. Meanwhile, regarding the final energy demand, there has been little progress in the process of switching from conventional fuel to hydrogen, etc. and accelerating electrification as much as possible.

However, such an energy utilization scheme appears impractical in view of high risks concerning the continued availability of ammonia and hydrogen from abroad and the stability of their prices. Moreover, the heavy reliance of final energy demand on electricity is problematic as it reduces the flexibility of the total society towards the high efficient utilization of energy.

Therefore, it is advisable to implement CCS as much as possible not only at industrial facilities but also at thermal power plants while trying to maintain the share of ammonia and hydrogen in power generation around 25%. In the final energy demand, the process of electrification should be properly balanced with the effort to introduce FCs, FCVs and other technologies that may contribute to higher energy efficiency or to the significant lowering of costs. An "optimal balance" in such contexts may be crucial.

The use of CO_2-free ammonia may reduce over-reliance on hydrogen power generation, contributing to a more balanced power mix. Although hydrogen and ammonia may compete with each other, each may find its own preferred fields of application depending on the characteristics of application devices and the scale of distribution systems. The two may be combined flexibly so as to maximize the advantages of each.

References

1) The Institute of Energy Economics, Japan, *Asia/World Energy Outlook 2016* (2016).
2) Japanese Ministry of Economy, Trade and Industry, *Long-Term Energy Supply and Demand Outlook* (2015).
3) Power Generation Cost Verification Working Group of the Advisory Committee for Natural Resources and Energy, *Report on Verification of Power Generation Costs, etc*. (2015).
4) Research Institute of Innovative Technology for the Earth (RITE), *Report on the Outcomes of R&D on Geological Carbon Dioxide Storage Technology* (2007).