Analysis on Hydrogen Economics Focusing on Automobile Fuel Production in Oil Refinery

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This paper presents an analysis on hydrogen economics focusing on automobile fuel production in an oil refinery in Japan. Hydrogen is a promising automobile fuel and the oil refining industry would play a big role in producing, distributing and retailing it because the industry constructed the supply chain of automobile fuels like gasoline and diesel oil in the past. The production of hydrogen for retail will much affect the operation of refining equipment because an oil refinery produces and consumes a huge amount of hydrogen in its operation. In this analysis, the authors developed a linear programming model expressing a detailed oil refining process and analyzed the optimal hydrogen production amount for retailing and its marginal production cost. Through the analysis, it was found that the hydrogen retail amount is determined in the operational balance between reforming, cracking and hydrogen production units. The upper limit of the production for retailing was estimated at around 12 billion Nm^3/year.

Keywords: Hydrogen, Petroleum Refining, Automobile Fuel, Linear Programming

1. Background and objectives

1.1. Background

As fuel cell vehicles made their market debut in December 2014, the full-fledged use of hydrogen as energy started. The Strategic Road Map for Hydrogen and Fuel Cells, released by the Council for a Strategy for Hydrogen and Fuel Cells in June 2014, calls for reducing the hydrogen price to hybrid vehicle fuel price levels or lower by around 2020 and FCV prices to hybrid vehicle price levels by around 2025.

In order to diffuse FCVs in the future, Japan will have to make hydrogen stably available at any location and time. The Japanese oil industry has supplied gasoline and diesel oil as automobile fuels and is expected to play a still more major role in supplying hydrogen[1)].

1.2 Objective

An oil refinery produces hydrogen with the catalytic reformer (RF) and hydrogen unit (HU) using liquefied petroleum gas and naphtha as materials and consumes hydrogen with hydrodesulfurization, hydrocracking and other units, balancing hydrogen production with consumption. If oil refineries become a major hydrogen supply source for FCVs, key challenges will include how hydrogen would be priced in comparison with gasoline and diesel and how much hydrogen would have to be shipped. Probably, oil refineries will determine production levels for hydrogen for FCVs while considering the balance between their in-house hydrogen consumption and their production of gasoline blending components and petrochemical materials (benzene, toluene and xylene).

This study uses an oil refinery LP (linear programming) model giving consideration to external hydrogen sales to find an optimal production volume for hydrogen for FCVs on the premise of capacity and operation levels for cracking and other secondary equipment and constraints on production volumes for petroleum products. Furthermore, this study aims to examine optimal shipment prices, using a shadow price and marginal production cost analysis. In addition, this

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study covers a sensibility analysis on refinery component operations for a case where growth in hydrogen production for FCVs would take the place of gasoline production and on how hydrogen production for FCVs would change due to the refining of heavier crude oil.

2. Study method and preconditions

2.1 Study method

Hydrogen for FCVs is presumed to be produced at oil refineries in Japan from 2020 through around 2030.

The refinery LP model is outlined below:

(i) Oil refinery LP model: One refinery for one country, optimization (maximizing profit)

(ii) Object function=∑((Shipment price)×(Product shipments))-∑((Crude oil receipts)×(Crude oil purchase price)+(Material purchase volume)×(Material purchase price))-∑(Catalyst and other chemical costs for various systems)

(iii) Model size: About 1,000 variables, about 930 constraints

2.2 Preconditions

(1) Major components

(i) Distillation unit:

Atmospheric distillation, Vacuum distillation

(ii) Desulfurization unit:

Desulfurization of naphtha, gasoline, kerosene and diesel oil; (vacuum) residue desulfurization

(iii) Cracking unit:

Hydrocracking, thermal cracking, catalytic cracking (including RFCC (residue fluid catalytic cracking))

(iv) Reforming unit:

Catalytic reforming, alkylation, isomerization, ETBE (ethyl tertiary butyl ether)

(2) Crude oil and material purchases

(i) Crude oil for refining:

Middle Eastern crude (light, medium and heavy), South East Asian crude, Condensate (up to 5% of crude oil receipts)

(ii) Material purchases:

ETBE, ethanol (material for ETBE production)

(3) Major petroleum products

(i) Gasoline (premium RON98, regular RON90)

(ii) Naphtha，LPG，BTX (benzene, toluene, xylene)

(iii) Petrochemical propylene

(iv) Jet fuel (including bond exports), kerosene

(v) Diesel oil (sulfur at 10 ppm), Fuel Oil A

(vi) Low sulfur (LS) fuel oil, medium sulfur (MS) fuel oil

(vii) High sulfur (HS) fuel oil, bunker, asphalt, petroleum coke

(4) Prices

The crude oil price is set at $100/bbl for WTI (West Texas Intermediate) and the exchange rate at 100 yen to the dollar.

(i) Crude oil price:

C&F (cost and freight) crude oil purchase price for a refinery

(ii) Petroleum product prices:

Prices for shipments from a refinery (MOPS (Mean of Platts Singapore) + freight)

(5) Quality and specifications of petroleum products

Quality and specifications are the same as at present. The biofuel (ETBE) blending ratio for gasoline is set at 7% (equivalent to 3% for ethanol).

(6) Hydrogen production and consumption

Figure 1 indicates the hydrogen production-consumption (including external sales) balance and the production flow for gasoline blending components and BTX. Hydrogen for FCVs will be collected with the purity being raised through the refining process.

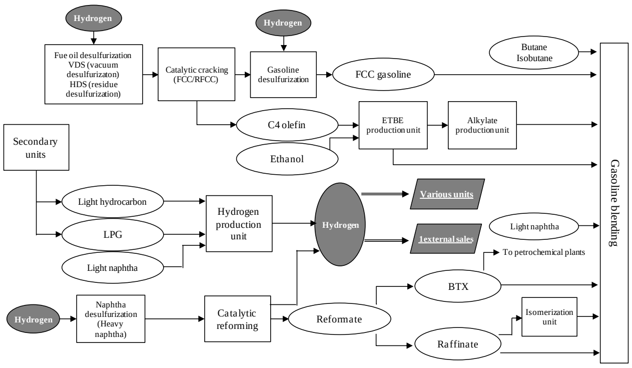

Figure 1 Hydrogen-gasoline blending component balance in the LP model

(7) Petroleum product production volume (shipment volume)

Petroleum product demand shown in Table 1 was estimated by the authors based on Book[2), etc. Based on the demand, production limits were set for gasoline and middle distillates (jet fuel, kerosene, diesel oil and Fuel Oil A). LPG, naphtha, bottom products (HSC (high-sulfur C-fuel) fuel oil, bunker oil, asphalt and petroleum coke), etc. were produced in line with the balance.

Table 1 Petroleum product demand assumptions

(Unit: 10,000kl)

Products	FY2010	FY2014	BASE case (This study)
Gasoline	5,816	5,298	4,991
Naphtha	4,670	4,392	3,830
Jet fuel	1,409	1,537	1,248
Kerosene	2,035	1,666	1,567
Diesel oil	3,289	3,358	3,109
Fuel Oil A	1,543	1,236	1,052
Fuel Oil C (excluding fuel for power generation)	1,117	815	441
Total for fuel	19,879	18,302	16,238
Middle distillate yield	42%	43%	43%

(Note) Results are from Book[3]. Jet fuel includes bonded production.

(8) Oil refining capacity

Table 2 indicates major capacity data for the refinery subject to the model. In this study (BASE case), capacity is assumed for the time after the first-phase (March 2014) and second-phase (March 2018) capacity reduction under the Energy Supply Structure Sophistication Act. As available data for the hydrogen unit (HU) are limited, the HU capacity is assumed at 12.6 billion Nm^3/year.

Table 2 Assumed oil refining capacity

(Unit: 1,000 barrels per day)

Equipment	Capacity		
	March 2010	March 2015	This study
Atmospheric distillation	4,616	3,947	3,400
Vacuum distillation	1,783	1,591	1,450
Catalytic reforming (RF)	867	815	700
Fluid catalytic cracking (FCC)	1,038	958	900
Heavy oil cracking	207	252	250
Kerosene and diesel desulfurization	2,258	2,072	1,800
(Vacuum) residue desulfurization	1,460	1,460	1,500
Alkylation	103	103	100

(Note) FY2009 results are from Book[4] (fuel oil desulfurization capacity is estimated by the authors). FY2014 data are estimated by the authors.

(9) Hydrogen purification

Hydrogen for FCVs must have a high purity of 99.99%. As hydrogen from the refinery fails to meet the purity requirement, the PSA (Pressure Swing Absorption) method is used for purifying hydrogen. The high-purity hydrogen collection rate for the PSA is set at 70%, with the cost assumed at 5 yen/Nm^3 (as estimated by the authors).

3. Results and analysis

3.1 BASE case (without production of hydrogen for FCVs)

Capacity utilization rates for the BASE case without production of hydrogen for FCVs are indicated in Table 3 and the refinery hydrogen supply-demand balance in Table 4. The capacity utilization rate for the atmospheric distillation unit is at 100%, the crude oil API gravity at 34.1, the sulfur content at 1.82% and the average import price at $108.4/bbl. The catalytic reformer produces 8.1 billion Nm^3/year and the hydrogen unit 7.2 billion Nm^3/year. About 90% of the hydrogen production is consumed for desulfurization.

Table 3 Capacity utilization rates in the BASE case

Equipment	Capacity utilization rate	Equipment	Capacity utilization rate
Atmospheric distillation	100%	Vacuum residue desulfurization	71%
Vacuum distillation	83%	Fluid catalytic cracking (FCC)	78%
Kerosene and diesel desulfurization	52%	Heavy oil cracking	85%
Residue desulfurization	48%	Catalytic reforming (RF)	59%

Table 4 Hydrogen supply-demand balance in the BASE case

(Unit: 100 million Nm^3/year)

Production	153	Consumption	153
Catalytic reforming (RF)	81	Hydrodesufurization	136
Hydrogen unit (HU)	72	Hydrocracking	14
		Others	3

3.2 Case with production of hydrogen for FCVs

We analyzed the case where production of hydrogen for FCVs increases with gasoline output kept unchanged. Figure 2 indicates the hydrogen shipment price and production of hydrogen for FCVs. Table 5 shows operational conditions of major equipment and the hydrogen supply-demand balance. As the hydrogen shipment price exceeds the crude oil purchase price (20 yen/Nm^3) for the refinery, production of hydrogen for

FCVs starts with the operation amounts rising for the RF reformer and hydrogen unit. Production increases gradually (the refinery's gross direct profit from refining rises proportionately).

An increase in the operation amount for the RF reformer leads to a rise in hydrogen generation. At the same time, reformate (RF output) production increases, resulting in an expansion in supply of gasoline blending components or petrochemical materials (BTX). Table 5 shows that a decline in the operation amount for the FCC unit leads to a drop in FCC gasoline supply while reformate supply increases. While an increase in the operation amount for the RF reformer results in a slight rise in hydrogen consumption for the desulfurization of heavy naphtha as material, a substantial fall in hydrogen consumption for the desulfurization of vacuum diesel oil and residue oil as materials for the FCC unit and that of FCC gasoline is coupled with an increase in hydrogen generation at the RF reformer to produce hydrogen for FCVs.

As indicated by Figure 2, production of hydrogen for FCVs greatly increases as the shipment price exceeds 60 yen/Nm^3. As the price surpasses 80 yen/Nm^3, however, production of hydrogen for FCVs slows down its rise and gradually increases close to about 12 billion Nm^3/year. This suggests limits on required production levels for gasoline blending components and BTX and HU capacity, and material constraints on LPG and naphtha in this study (BASE case).

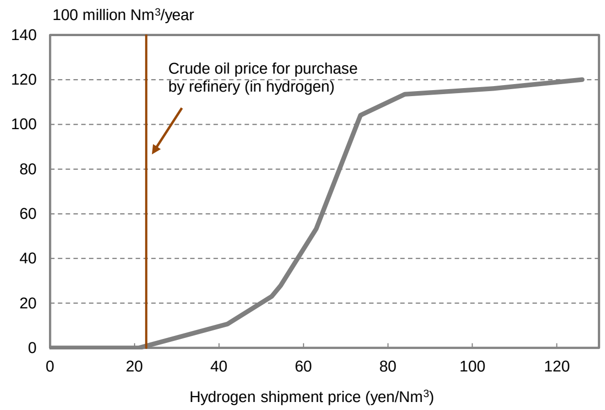

Figure 2 Trends of production of hydrogen for FCVs and the shipment price

Table 5 Changes in the shipment price of hydrogen for FCVs and equipment operation

	Cases for this study			
	BASE	A1	A2	A3
Hydrogen shipment price (yen/Nm^3)	21	42	63	84
Gross direct profit from refining (objective function) (100 for BASE case)	100	100	104	117
Reformer operation amount (100 for BASE case)	100	102	110	119
Catalytic cracking unit operation amount (100 for BASE case)	100	97	83	66
Hydrogen production (100 million Nm^3/year)	153	155	189	231
Reformer	81	83	89	94
HU unit	72	72	100	136
Hydrogen consumption (100 million Nm^3/year)	153	155	189	231
In-house consumption	153	140	113	68
Shipments of hydrogen for FCVs (100 million Nm^3/year)	0	11	53	113

Table 6 indicates production of hydrogen for FCVs and equipment operation conditions in the case for heavier crude oil. As residue and other desulfurization units increase their operations due to heavier crude oil, hydrogen shipments at the same price decrease. If crude oil API gravity increases to 31.6, the sulfur content of imported crude oil rises by about 0.3 points from the BASE case and the operation amount of the residue desulfurization unit by 30%. Given that the residue desulfurization unit is one of the refinery components that consume hydrogen most heavily, an increase in its operation amount leads to a decline in production of hydrogen for FCVs.

Table 6 Heavier crude oil and equipment operation conditions

	Cases for this study			
	BASE	B1	B2	B3
Crude oil API gravity	34.1	34.2	32.3	31.6
Hydrogen shipment price (yen/Nm^3)	21	53		
Residue desulfurization unit operation amount (100 for BASE case)	100	100	116	129
Catalytic cracking unit operation amount (100 for BASE case)	100	92	96	97
In-house hydrogen consumption (100 million Nm^3/year)	153	124	138	149
Production of hydrogen for FCVs (100 million Nm^3/year)	0	23	12	4

3.3 Shadow price and marginal cost of hydrogen production for FCVs

With the shipment price of hydrogen for FCVs set at 55 yen/Nm^3, optimization calculation was conducted with production of hydrogen for FCVs fixed at various levels to compute the shadow price regarding the production volume constraint of hydrogen for FCVs. If the hydrogen shipment price exceeds cost levels for various production volumes, the shadow price is positive. If the shipment price is below cost levels, the shadow price is negative. When the shipment price is appropriate, the shadow price is zero. This means that the marginal production cost is defined as a preset shipment price minus the shadow price. Marginal cost levels computed for various production levels are illustrated in Figure 3. However, gasoline production is assumed to decline in line with a rise in production of hydrogen for FCVs (with a fuel economy gap between FCVs and gasoline-fueled vehicles taken into account). As gasoline production is not fixed at any level, operational conditions of refinery components may change (with the production balance changing). Therefore, production may not necessarily continuously change in line with the marginal cost curve.

In Area (A) in Figure 3, the shadow price is positive, meaning that growth in hydrogen production leads to a rise in gross direct profit from refining. In Area (B) where the shadow price is negative, growth in hydrogen production leads to a decline in gross direct profit from refining. At the point (indicating a production level of 2.5 billion Nm^3/year) where the shipment price curve crosses the marginal cost curve, the shadow price becomes zero with hydrogen production working to maximize gross direct profit from refining.

Meanwhile, marginal cost changes in Figure 3 are explained by operational conditions of refinery components as follows: In a stage where production of hydrogen for FCVs remains low, the operation amount stays unchanged for the HU unit while increasing for the RF unit with hydrogen consumption for desulfurization reduced to provide hydrogen for FCVs. As the operation amount for the HU unit increases gradually, the marginal cost rises to about 60 yen/Nm^3. The cost may moderately increase before jumping sharply as hydrogen production reaches the HU capacity limit or a material constraint level.

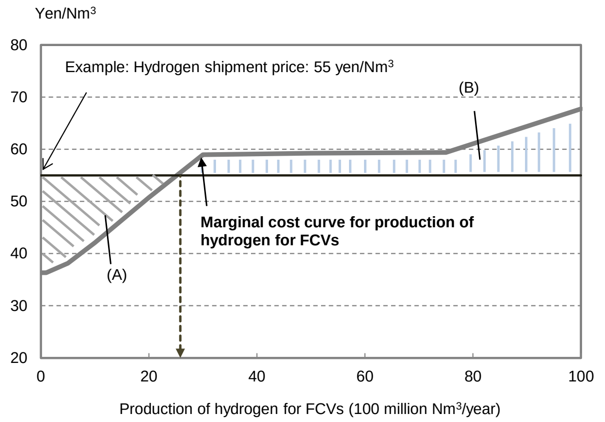

Figure 3 Shadow price and marginal cost of hydrogen production for FCVs

(Note) The above shipment price includes a PSA cost at 5 yen/Nm^3.

Figure 4 indicates the marginal cost curve for heavier imported crude oil with an API gravity of about 32. As noted in Section 3.2, heavier crude oil brings about an increase in the operation amount of the desulfurization unit, reducing room for production of hydrogen for FCVs. As the LPG-based hydrogen unit accelerates its operation, the marginal cost curve shifts leftward.

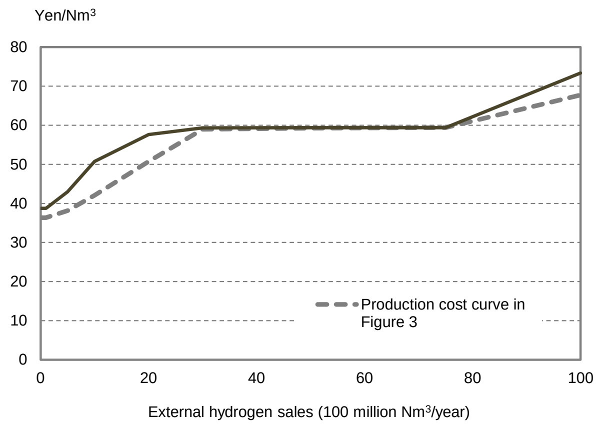

Figure 4 Marginal production cost changes for heavier crude oil

4. Conclusion

We implemented an analysis on the economics of hydrogen production, using an oil refinery LP model giving consideration to shipments of hydrogen for FCVs. While analysis results changed depending on crude oil prices and equipment capacity, we made the following findings:

(i) Production of hydrogen for FCVs depends on

gasoline and BTX production, hydrogen unit capacity and the availability of raw materials for hydrogen generation.
(ii) Optimum production volume for hydrogen for FCVs is 2-8 billion Nm^3/year.
(iii) The shipment price of about 60 yen/Nm^3 and the shipment volume of 5 billion Nm^3/year could be a standard for supply of hydrogen for FCVs.

Reference

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