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Estimation Method for the Creation of Hydrogen Stations with Woody Biomass and Livestock Excreta in Japan

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Abstract – *It was determined that woody biomass and livestock excreta can be utilized as hydrogen resources, and hydrogen produced from such sources can be used to fill fuel cell vehicles (FCVs) at hydrogen stations. It was shown that the biomass transport costs for hydrogen production may be reduced by as much as 20% of the costs for co-generation. In the Tokyo Metropolitan Area, there are only a few sites capable of producing hydrogen from woody biomass in amounts greater than 200* m^3/h*—the scale required for a hydrogen station to be operationally practical. However, in the case of livestock excreta, it was shown that 15% of the municipalities in this area are capable of securing sufficient biomass to be operationally practical for hydrogen production. The differences in feasibility of practical operation depend on the type of biomass. Furthermore, it was also shown that the method of hydrogen production from livestock excreta can be economically feasible with the effect on reduction of* CO_2 *emission in the future.*

Keywords – Biomass resources, hydrogen production, hydrogen station, transport cost.

1. INTRODUCTION

Biomass is carbon neutral, because biomass fixes carbon dioxide by photosynthesis even though carbon dioxide is released into the atmosphere by combustion. The majority of biomass conversion processes involve co-generation or a combined heat and power system. The reality, however, is that little progress is being made towards real-world use. Regarding co-generation with biomass, therefore, large-scale operations and heat demand exists are necessary for improving total energy efficiency. Another factor that may hinder the utilization of biomass is the economic challenge of its collection and transport. It suffers disadvantages in that it is present in low densities over a broad geographic range.

Along with growing public awareness of the environmental impact of energy (such as in the cases of issues like global warming and the depletion of fossil fuels), hydrogen energy is attracting attention as a secondary energy form that has excellent future potential. Although hydrogen exists naturally only in small amounts, as secondary energy, it may be produced from a variety of primary energy sources. It is also the only energy source capable of inter-conversion with electric power, and it is an extremely clean form of energy in that its combustion produces only water. Among the many methods of producing hydrogen are steam reforming with petroleum, natural gas, or biomass, water electrolysis, and the utilization of by-product hydrogen obtained from petroleum refining or coke production processes. However, the entire process from production of raw materials through hydrogen production may entail the emission of large volumes of carbon dioxide. Its adoption must be carefully and considered, taking into account factors such as life-cycle assessment (LCA) techniques [1]. Hydrogen production from biomass is extremely advantageous in LCA terms over numerous other methods of hydrogen production [2], [3].

If it is possible to produce hydrogen efficiently from biomass, it could be expected that the utilization of biomass would become more widespread with the use of hydrogen energy as a medium for transportation and storage.

2. METHODS OF HYDROGEN PRODUCTION FROM BIOMASS IN JAPAN

Table 1 summarizes the methods of producing hydrogen from biomass that have been demonstrated or developed for practical use in Japan to date. The sources of biomass are divided into the two types of "dry" and "wet." Produced methane with some conversion methods in the table should be converted to hydrogen by steam reforming (see remarks). As for the scale of the conversion plants in the table, data for small laboratory plants is also included. The hydrogen recovery rate of pressure swing adsorption (PSA), which is adopted for separate hydrogen from produced gas, is estimated at 80% on high-pressure specification.

3. BIOMASS COLLECTION AND TRANSPORT COSTS

One of the factors requiring the most consideration in promoting the utilization of biomass is how to reduce the costs involved in collection and transportation. Since biomass is present in low densities over a broad geographic range, reducing related collection and transportation costs requires consideration of how to collect the biomass and transport it to sites efficiently. In general, the distance from forest to hydrogen station is shorter than that to co-generation site, because heat demand in co-generation sites is only fulfilled at large-scale factories such as dairy farms or sawmills.

Taking as an example co-generation with woody biomass on a scale of 100 tons daily, Table 2 summarizes

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the collection and transportation costs for biomass according to a METI report [9].

Transport cost B to the location of a co-generation site, where electric power and heat consumptions are adequate, is high and accounts for some 30% of the total cost.

Table 3 shows the relationship between transport distance and transport cost B, according to the METI report. A transport cost B at a transport distance of around 60 km is indicated in Table 2. Using Table 3, one can calculate transport costs for various transport distances.

This table indicates that transport costs may be marginally reduced within a transport range of 10 km.

4. POSSIBILITIES FOR HYDROGEN PRODUCTION FROM BIOMASS IN MOUNTAINOUS TOWNS AND VILLAGES IN THE KANTO DISTRICT

Working towards the establishment of a hydrogen society, the Japanese government currently has a propagation plan in which the primary component is fuel-cell vehicles (FCVs) (See Figure 1).

Table 1. Methods of hydrogen production from biomass in Japan.

Sources of biomass		Conversion technique	Gas composition, energy efficiency, etc.	Scale and remarks	Ref No.
Dry	Woody biomass (forest cuttings, thinned wood, sawmill scrap, etc.)	Low temperature fluidized-bed gasification	H_2: 66%, CH_4: 2%, cold gas efficiency: 70%	B: 10 t/d (dry)	[4]
		Partial-oxidation gasification	H_2: 62%, cold gas efficiency: 60%	B: 10 t/d (dry)	[4]
		Steam gasification	H_2: 60%, 17 m^3/h (H_2)	B: 1.4 t/d (wet)	[5]
			H_2: 83%, CH_4: 15%, 0.5 m^3/h (H_2)	B: at 1 g/h (laboratory)	[6]
	Grasses, seaweed	Supercritical-water gasification	H_2: 10% or less, CH_4: 45%	CH_4 reforming req.	[4]
	Agricultural waste	Dry methane fermentation + steam gasification	CH_4: 60%, CO_2: 40%, 150 m^3/t wet, 21.5 MJ/m^3	B: 50 t/d (wet); raw waste CH_4 reforming req.	[7]
	Waste paper, grass	Hydrogen fermentation, methane fermentation + steam gasification	H_2: 5.23 mol/dry-kg CH_4: 8.39 mol/dry-kg	Estimate from NEDO process (grass)	[8]
Wet	Livestock excreta, food waste, sewage sludge	Methane fermentation + steam gasification	CH_4 fermentation: 40% energy efficiency, reform: 67% heat efficiency	B: 10 t/d (dry); CH_4 reforming req.	[4]
		Hydrogen fermentation, methane fermentation + steam gasification	H_2: 2.95 mol/dry-kg CH_4: 8.57 mol/dry-kg	Estimate from NEDO process	[8]
	Sewage sludge, food waste	Supercritical-water gasification	H_2: 10% or less, CH_4: 50%	CH_4 reforming req.	[4]

Pressure swing adsorption (PSA) hydrogen recovery rate: 80% (high-pressure spec)

Table 2. Biomass collection and transport costs.

Condition		Costs (yen/ton)
Standing timber price (thinned wood)		5,900
Logging & collection costs		4,000
Transport costs	Cost A (loading place to collection yard)	3,100
	Cost B (collection yard to end-use location); the distance is about 60 km	5,300
Total cost		18,300
Cost B ratio（%） = Cost B / total cost		30%

Table 3. Relationship between transport distance and transport cost B.

Transport distance	Transport cost B
$x \leq 10$ km	230.3 yen/km・t
10 km $< x \leq$ 50 km	57.9 yen/km・t + 1,724yen/t
50 km $< x \leq$ 100 km	50.6 yen/km・t + 2,090yen/t
100 km $< x \leq$ 200 km	31.4 yen/km・t + 4,010yen/t
200 km $< x \leq$ 500 km	27.5 yen/km・t + 4,790yen/t
500 km $< x$	27.7 yen/km・t + 4,690yen/t

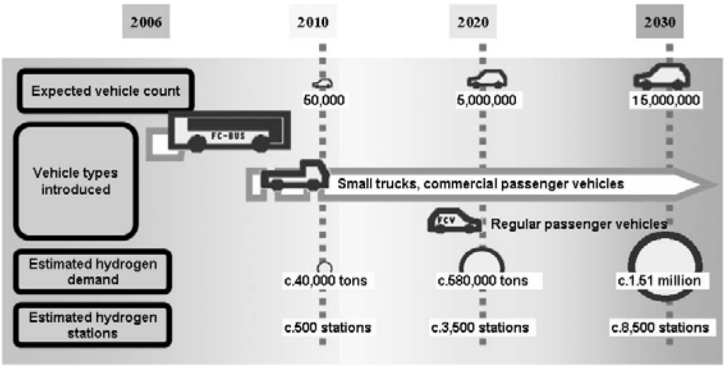

Fig. 1. FCV propagation targets.

Given the issues of biomass collection and transportation, one may conceive of methods utilization in which hydrogen is produced at sites at which biomass is converted to hydrogen and FCVs are refilled at hydrogen stations, thus allowing reduction of the ratio of cost B in the table. Where,

Q: Volume of utilizable biomass (tons/year);

Q_w: Volume of utilizable woody biomass;

i: Type of woody biomass (forest cuttings, sawmill scrap, orchard prunings, park prunings);

$Q_w = \sum Q_i$;

Qs: Volume of utilizable livestock waste;

j: Type of livestock waste (dairy cow excreta, meat cattle excreta, hog excreta, poultry manure);

$Q_s = \sum Q_j$;

S: Municipal area (km^2);

N: Current petrol station count (locations); and

ρ: Proportion converted to hydrogen stations (%); the volume of utilizable biomass q (tons/day) per hydrogen station will be

$q = Q / [(N\rho/100)360]$.

Further, where annual hydrogen plant downtime is five days (1 day of periodic maintenance and four annual holidays), the biomass collection areas (km^2) per hydrogen station location will be:

$$s = S / (N\rho/100) \qquad (1)$$

and the average biomass transport distance (km) L will be:

$$L = 10[S / (N\rho\pi)]^{1/2} \qquad (2)$$

Where hydrogen stations are constructed at multiple locations in a municipality, as in Figure 2, the biomass service area may be segmented simply and distance L calculated as its radius and understood as the average distance from biomass loading place to collection yard to end-use location in Table 2 for woody biomass. The distance from collection yard to end-use location corresponding to transport cost B is thus shorter than distance L.

The required production volume for a commercialized hydrogen station is calculated at a minimum of 200 m^3/h [13]. Therefore, it is discussed below whether the calculated volume of hydrogen produced from biomass is above such figure or not.

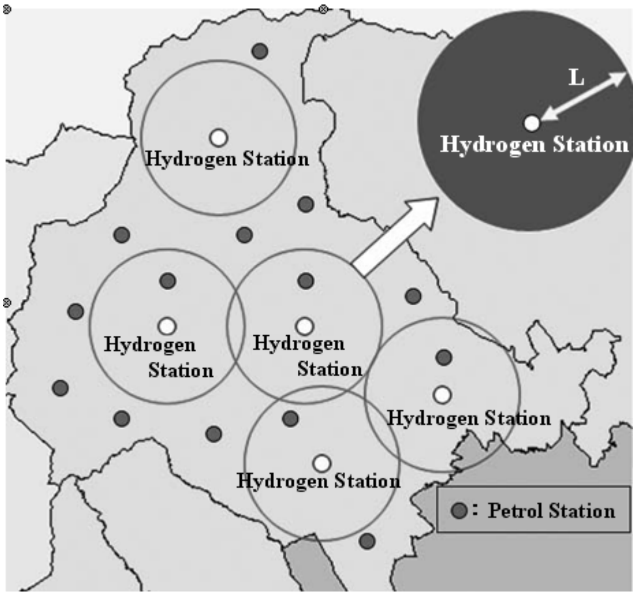

Fig. 2. Biomass transport distance L.

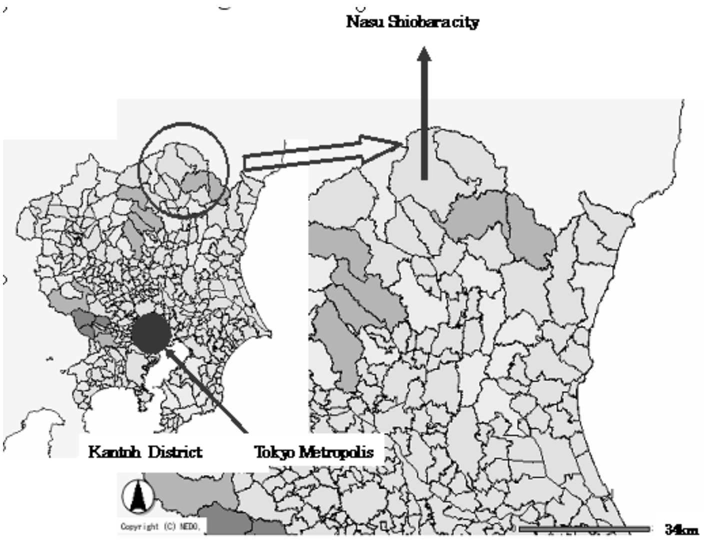

Fig. 3. Location of Nasu Shiobara City, Tochigi Prefecture.

i. *Example of Nasu Shiobara City in Tochigi Prefecture*

The city of Nasu Shiobara in Tochigi prefecture is a Kanto district municipality in which wood is particularly available.

Calculating for woody biomass, we find:

$Q_w = \Sigma Q_i$

$= 196.45$ (forest cuttings) $+ 362.17$ (sawmill scrap)
$+ 73.69$ (orchard prunings)
$+ 195.04$ (park prunings)
$= 827.36$ tons/year (wet base)

This volume of utilizable biomass employs data from NEDO, "Estimates of Biomass Availability and Utilizable Volume" [10], [11]. Petrol station location figures have been obtained from the Value Management Institute, Inc. and Tokyo Gas [12].

Given $S = 592.45$ (km^2); $N = 80$ (locations); $\rho = 10\%$ (3,500 hydrogen station locations for 5 million FCVs in 2020); and $q = Q/ [(N\rho/100)360]$, the volume of utilizable woody biomass q per hydrogen station location will be:

$q = 0.29$ tons/day.

Processing this biomass with steam gasification and Pressure Swing Adsorption (PSA) refining using the data of reference [5] in Table 1 would yield 8.40 m^3/h of hydrogen.

Given $L = 10[S/ (N\rho\pi)]^{1/2}$

the average biomass transport distance in this case would be:

$L = 4.86$ km.

At a transport cost of 1,119 yen per ton and a transport cost B ratio of 7.9%, the advantage over co-generation (about 30%) is evident. One may expect a reduction in transport costs of close to 20%.

Calculating likewise for livestock excreta, we find:

$Q_s = \Sigma Q_j$

$= 25{,}917.59$ (dairy cow excreta)
$+ 3{,}988.17$ (meat cattle excreta)
$+ 1{,}205.86$ (hog excreta)
$+ 9{,}282.68$ (poultry manure)
$= 40{,}404.3$ tons/year (wet base)
$= 8{,}080.86$ tons/year (dry base, 80% water content)

$N = 80$ (locations)

$\rho = 10\%$ (for 5 million FCVs in 2020)

Thus, where

$q = Q/ [(N\rho/100)360]$

The volume of utilizable livestock excreta q per hydrogen station location will be:

$q = 4.86$ tons/day.

Calculation for this biomass using the data of reference [4] in Table 1 with methane fermentation, steam gasification, and PSA refining would yield 72.49 m^3/h of hydrogen.

The required production volume of hydrogen for a commercialized hydrogen station is defined as a volume corresponding to the volume of gasoline used to fill gasoline-operated vehicles at existing petrol stations, and preliminary calculations indicate a level of 200-300 m^3/h is sufficient to obtain profitability [13].

While slightly lower than this number, hydrogen production from livestock excreta in this area may be estimated to be more realistic than hydrogen production from woody biomass.

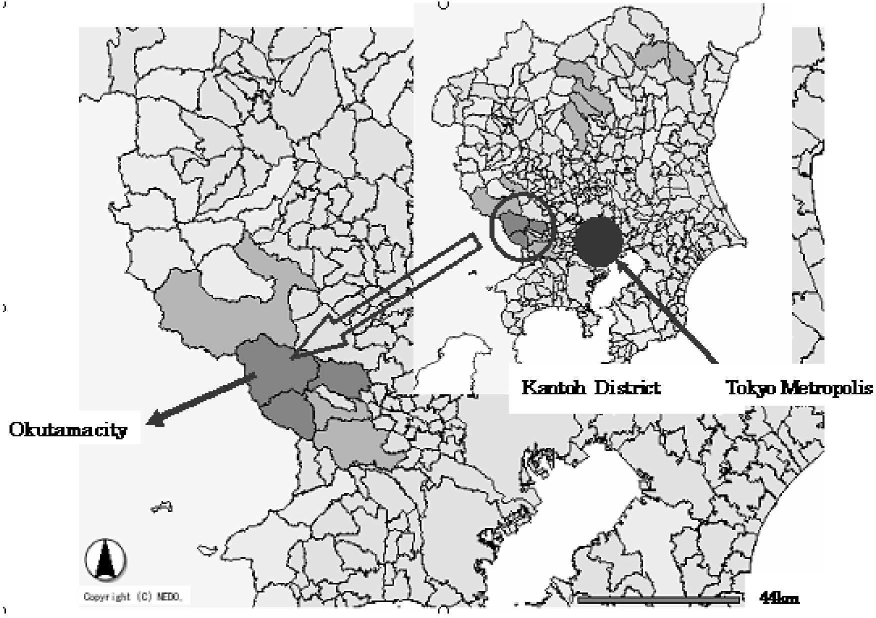

Fig. 4. Location of Okutama City, Tokyo-to.

ii. Example for Okutama City in Tokyo-to

The trial calculation below addresses a relatively remote forestry district where a few petrol stations currently exist. This city in the Kanto district offers excellent availability of woody biomass. Because there is no available source of livestock excreta in the city, only calculations for woody biomass are carried out.

$Q_w = \Sigma Q_i$

= 1,384.21 (forest cuttings)
+ 12.42 (sawmill scrap)
+ 25.36 (orchard prunings)
+ 0 (park prunings)
= 1,421.99 tons/year (wet base)
$S = 225.69\ km^2$
N = 5 (locations)
$\rho = 10\%$
Thus, where

$$q = Q/\ [(N\rho/100)360]$$

the volume of utilizable woody biomass q per hydrogen station location will be:

$$q = 7.90 \text{ tons/day}.$$

Utilizing steam gasification and PSA refining using the data of reference [5] in Table 1, this biomass would yield 230 m^3/h of hydrogen.

Therefore, this district may be estimated to have enough potential to develop a hydrogen station business based on production of hydrogen from woody biomass.

The maximum biomass transport distance in this instance will be:

$$L = 10(s/N\rho\pi)^{1/2}$$

and thus,

$$L = 11.99 \text{ km}.$$

Transport cost comes to 2,418 yen per ton, and the ratio of transport cost B is calculated as 15.7%. In this district as well, there are advantages over co-generation in terms of transport costs.

5. BIOMASS HYDROGEN STATION OPPORTUNITIES IN THE KANTO DISTRICT

As discussed above, we find that the production of hydrogen from biomass and the filling of FCVs at hydrogen stations is a more promising approach than co-generation with biomass. It is also clear that the form of its emergence will differ based on biomass type and the municipality in which it is developed.

This section considers the application of this approach in municipalities throughout the Kanto district.

Figure 5 shows the relationship, in 398 municipalities in the district, between volume of hydrogen production and biomass transport distance, using provisional calculations for the same conditions as employed above.

It can be noted from Figure 5 that hydrogen stations are required at no more than six locations to satisfy the requirement of minimum hydrogen station production volume of 200 m^3/h for practical woody biomass applications.

Figure 6 describes the relationship between transport distance and the number of station locations. Since a majority of stations (373 of 398 locations, or 93.7%) are located within a transport distance of 10 km, allowing large reductions in transport costs, it is possible to increase the number of stations capable of achieving practical application by further expanding the collection area for woody biomass to optimize economies.

Figure 7 plots the data for livestock excreta under the same conditions. It shows about 15% (53 of 359 locations) of all stations achieving 200 m^3/h or more and that production of hydrogen from livestock excreta is the more feasible method.

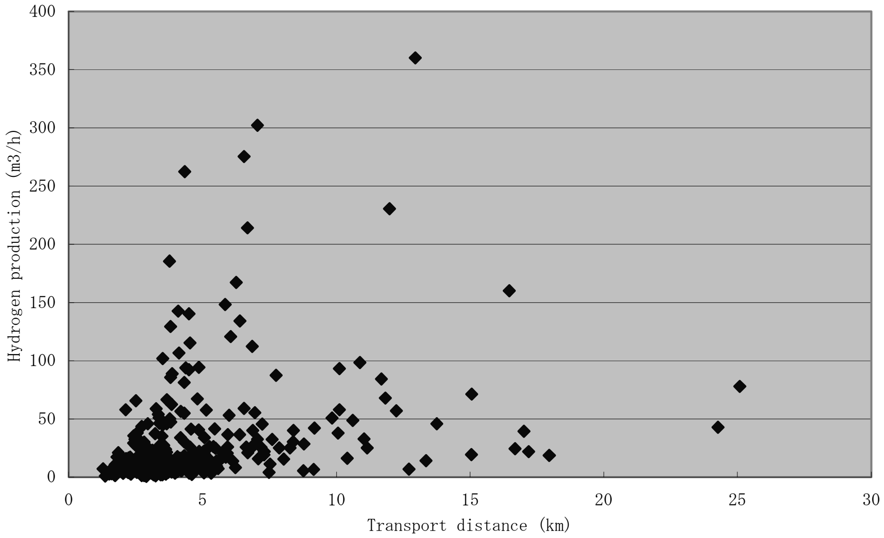

Fig. 5. Relationship between biomass transport distance and hydrogen production volume (woody biomass).

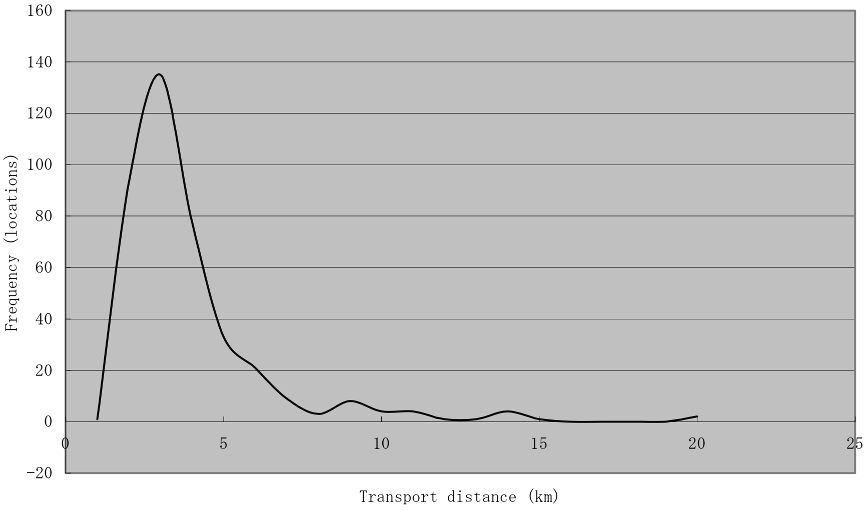

Fig. 6. Relationship between transport distance and service locations (woody biomass).

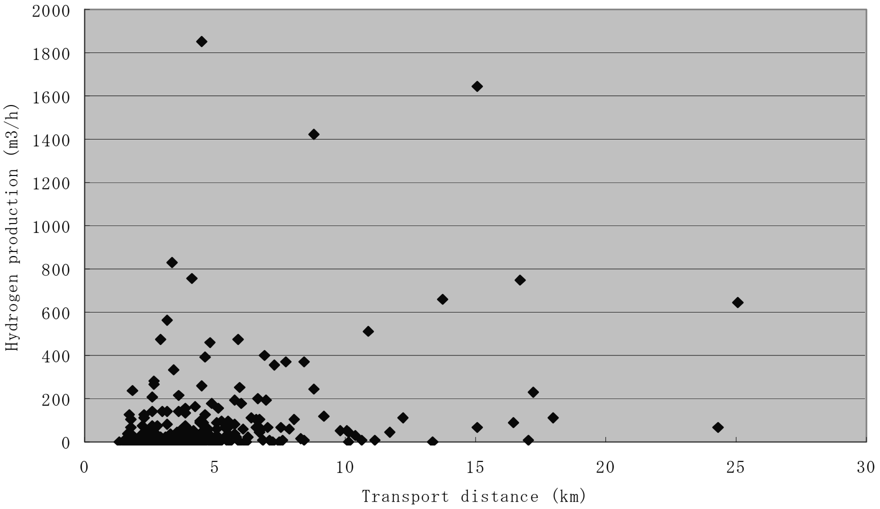

Fig. 7. Relationship between biomass transport distance and hydrogen production volume (livestock excreta).

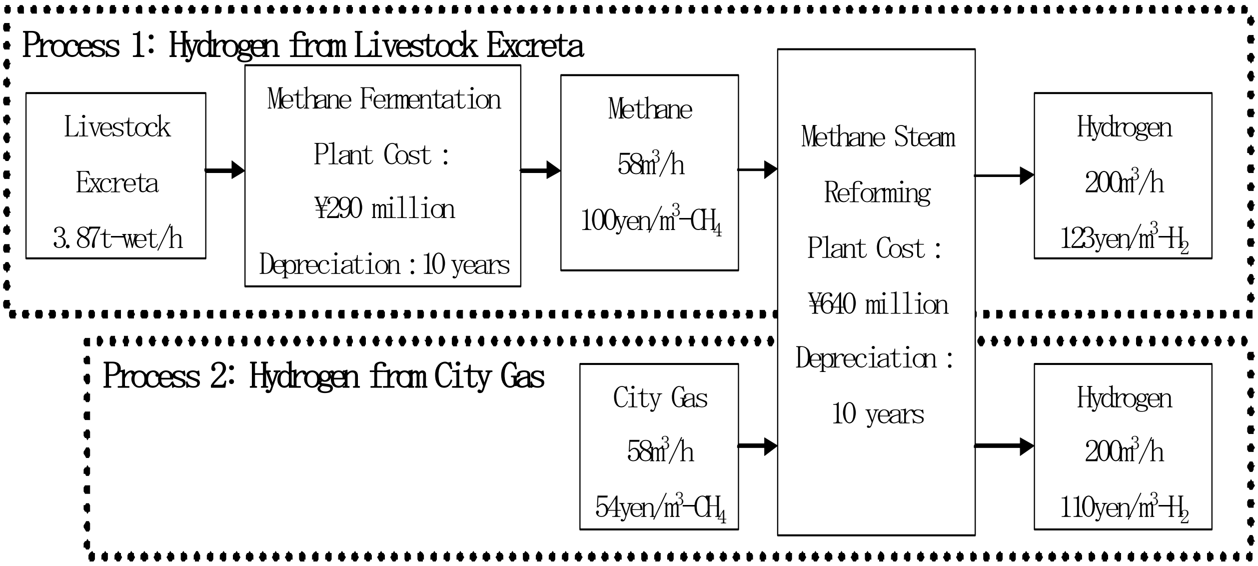

Fig. 8. Economic comparison of hydrogen production processes from livestock excreta and city gas.

6. ECONOMIC EVALUATION OF HYDROGEN STATIONS

It is investigated in the preceding chapters that the method of hydrogen production from biomass will be available to reduce biomass transportation cost as compared to that of co-generation using biomass. Then, economic benefits of installing hydrogen stations using biomass are discussed as follows.

The process of hydrogen production from livestock excreta is compared with that from city gas. Hydrogen production from city gas is recognized as a main process in the primary stage of formation of hydrogen society discussed in this paper in around 2020. The economic and material balance in both processes is indicated in Figure 8 [14], [15].

Assumptions in the comparison:

1. The cost calculated in Figure 8 is based in 2005.
2. The raw material cost of livestock excreta is estimated as an income of 1,000yen/t because existing disposal cost of livestock excreta can be reduced due to the introduction of this process.
3. The cost of methane gas purification (removal of CO_2, H_2S, and so on) is included in the plant cost of methane fermentation.
4. Benefits of residue liquid as fertilizers are not evaluated.

Hydrogen cost by process 1 (hydrogen production from livestock excreta) is 13 yen/m^3-H_2 higher than that by process 2 (hydrogen production from city gas) due to the significant plant cost of the methane fermentation.

However, the method in the process 1 can reduce 130kg-CO_2/h of CO_2 emission as compared to that in process 2 [1]. One can assume that CO_2 credit price will be 15 - 30 thousand yen/t-CO_2, and then it can be estimated 9.8 - 20 yen/m^3-H_2 reduction of hydrogen cost in process 1.

Therefore, the process of hydrogen production from biomass (livestock excreta) can be feasible, if the effect on reduction of CO_2 emission is evaluated economically in the future.

7. CONCLUSIONS

This paper examines approaches to the utilization of biomass by means of producing hydrogen from biomass and filling FCVs at hydrogen stations.

The following conclusions have been reached:

1. It was shown that hydrogen production from biomass allows large reductions in biomass transport costs below those for co-generation with biomass. The transport costs may be reduced by as much as 20% of collection and transport costs for co-generation.
2. There are no more than a few sites in Tokyo Metropolitan Area capable of hydrogen production of at least 200 m^3/h—the scale that is required for a hydrogen station to be operationally practical using woody biomass.
3. In the case of livestock excreta, it was shown that 15% of the municipalities in the Kanto district are capable of securing sufficient biomass to be operationally practical for hydrogen production. It was found that differences in feasibility of practical operation depend on biomass type.
4. It was also shown that the method of hydrogen production from livestock excreta can be economically feasible with the effect on reduction of CO_2 emission in the future.

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