Quantitative Analysis of CO_2 Emission Reduction by Introducing Stationary Type PEM-FC Systems in Japan

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Abstract

Fuel cell technology is expected to contribute to mitigate CO_2 emission in Japan. However, detailed quantitative analyses have not been done. This study analyzes the changes in energy consumption and accompanying CO_2 emission by the penetration of PEM-FC cogeneration systems in Japan quantitatively by taking dynamic changes in power generation mix into account. The Optimal Generation Mix Model (OPTIGEN) developed by CRIEPI is used for this calculation. The result shows CO_2 emission of overall energy system is divided into decreased cases and increased cases, compared with the reference cases. Key factors of it are development of nuclear power and technical progress in efficiencies of PEM-FC systems in future.

1. Introduction

Many automobile manufacturers have been fighting desperately for developing fuel cell vehicles currently. Its core technology called the Proton Exchange Membrane Fuel Cell (PEM-FC) can be used as a cogeneration system in a house, and some researchers indicate the penetration of PEM-FC as stationary cogeneration systems (see Fig. 1) will be even faster than as fuel cell vehicles in Japan, because of many reasons. One of the reason is that required capacity for a stationary system is much smaller than for a vehicle system, and the other reason is that existing fuel supplying infrastructures are already exists. The advisory panel set by the Japanese government treats fuel cells as one of the measure for mitigating CO_2 emission and set up a target to penetrate toward 2020 (see Table 1).

Table 1. Cumulative amounts of the target of PEM-FC systems

Type / Year	2010	2020
Automobile	50 thousand cars	5 million cars
Stationary system	2.1 GW	10 GW
Residential sector	1.2 GW	5.7 GW
Commercial sector	0.9 GW	4.4 GW

Source: FCDIC [1]

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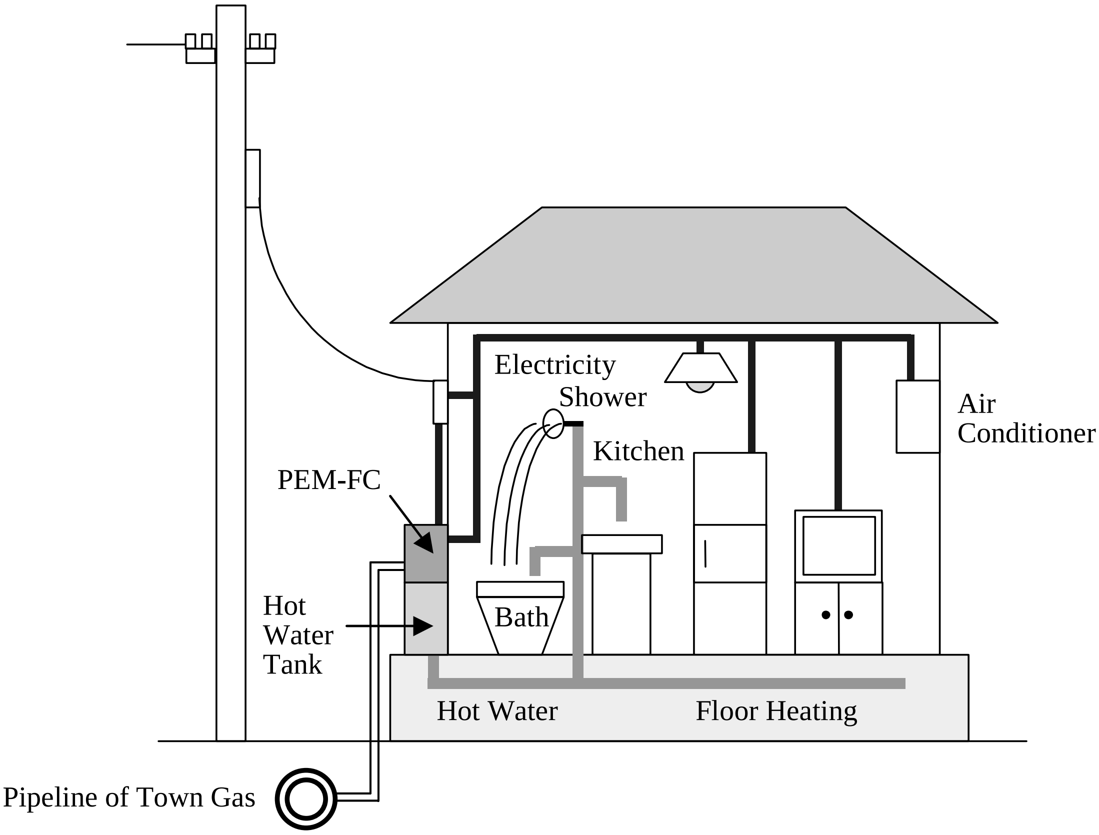

Fig. 1. An image of a PEM-FC stationary cogeneration system

However, detailed quantitative analyses have not been done yet. Developers of PEM-FC and town gas suppliers have done preliminary analyses, but all of them estimate the CO_2 emission from electric utility based on a static power generation mix. This method is not appropriate because dynamic changes in power generation mix will affect CO_2 emission from electric utility seriously. So the purpose of this study is to analyze the changes in dynamic changes in power generation mix and accompanying CO_2 emission by the penetration of PEM-FC cogeneration systems in Japan quantitatively.

2. Energy situation and fuel cells in Japan

Japanese economy has been facing a very long-term recession from the 90's; average growth rate of real GDP from 1991 to 2001 is only 1.0% per year. Energy demand in the same period has recorded only 0.9% per year increase. This is considerably small under the stable energy prices. Crude oil price imported in Japan has been $20-30 per barrel recently, which is almost same level before the first oil crisis happened in 1973 in real term. No bright outlook is also made in future. According to the outlook done by CRIEPI in April 2003, average growth rate of real GDP from 2000 to 2010 will remain 0.8% (Hattori et al [2]). One of the reasons of this low growth is the decrease in population after 2006. Energy and electricity (not including self-generation) demand in the same period are forecasted to be -0.1% and 1.1% respectively.

On the other hand, the Japanese government ratified the Kyoto Protocol and is obliged to control green house gases to 94% of 1990 level in 2010. As for CO_2 emissions from energy sources, a target of stabilizing to 1990 level was authorized in March 19, 2002 (Japanese government [3]). To achieve this target is quite difficult, because CO_2 emissions from energy sources in 2001 were 6.3% greater than the levels in 1990. Thus, it is really a tough work to mitigate it to the 1990 levels in 2010, although several countermeasures to strengthen efficiency standards of appliances and vehicles, and to accelerate introduction of renewable energy sources have been already enforced.

As for electricity market, liberalization process has been also in progress in Japan. In March 2000, retail sale to the largest scale customers (over 2000 kW), which occupies about 30% of total electricity demand, was liberalized. This range is planned to expand to 60-70% (customers over 50 kW) in April 2005. It is expected that competition between new suppliers and existing electric utilities will become stronger over the low growth electricity market.

According to the situations described before, fuel cell technology gathers many hopes in Japan. One of these is that it would be a new countermeasure for the government to mitigate CO_2 emission from buildings and transportation sectors. Other hope is that it would be a powerful appliance for gas and oil suppliers to snatch electricity market and enlarge their sales. Moreover, manufacturing fuel cells is considered to be an important new industry to Japan in near future.

Major electric appliance manufacturers, gas suppliers, and oil companies in Japan make a target to sell PEM-FC cogeneration systems in 2005 at around 500 thousand yen (a subsidy is accounted) and it is expected to save energy expenses by 30-50 thousand yen annually. A hot water supply appliance costs around 200 thousand yen and this cost will be avoided for newly constructed house. As a result, initial cost-up can be paid back within 6-10 years, if their target will be achieved.

3. Procedure

Overall procedure of the study is shown in Fig. 2. First, technological condition, operating pattern, and penetration rate are estimated from other reports. Decreases in electricity demand for utility by year, representative days, and each hour are calculated according to these conditions. Then the Optimal Generation Mix Model (OPTIGEN) calculates the optimal power expansion and operating plan for each demand scenarios. At the same time, CO_2 emission from electric utility is obtained. Finally, CO_2 emission from PEM-FC systems and changes in total emission with utility and PEM-FC systems are calculated.

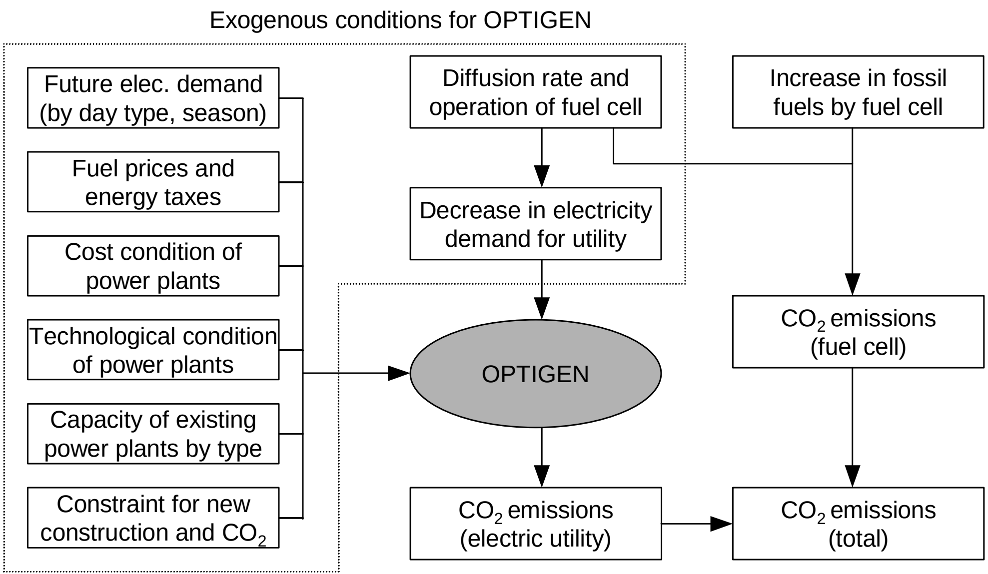

Fig. 2. Procedure of the Study

4. Optimal Generation Mix Model (OPTIGEN)

Optimal Generation Mix Model (OPTIGEN) is a mathematical planning model using the Linear Programming (LP) technique and was originally developed in 1996 (Takahashi et al [4]). It calculates an optimal plan that minimizes the total discounted cost to develop power plants and to operate them through a certain planning period (typically 20-30 years). One of the important advantages of OPTIGEN is its flexibility. The following factors can be easily changed according to the purpose of the study when OPTIGEN is used:

- Country or region
- Planning period and its calculated interval
- Choice of day type and season
- Facility type and technology
- Extension of plant life
- Calculation platform (with the General Algebraic Modeling System (GAMS))

Objective function considered in the model is as follows:

Objective function: $$TC = \sum_{T=0}^{T_N} R_T \times \sum_{G} \left(CF_{G,T} + CV_{G,T} \right) \quad (1)$$

$$CF_{G,T} = \sum_{T=0}^{T_D} f_{G,T} \times K_{G,T} \quad (2)$$

$$CV_{G,T} = v_{G,T} \times \sum_{DAY} N_{DAY} \sum_{HR} X_{G,T,DAY,HR} \quad (3)$$

where TC is the sum of discounted total cost until the end of planning period T_N, $CF_{G,T}$ and $CV_{G,T}$ the fixed cost and variable costs of power generation of power resource G in a period T respectively, R_T the conversion coefficient for the present value derived from a discount rate, and $f_{G,T}$ and $v_{G,T}$ the unit fixed cost and variable cost, respectively. T_D is the period of depreciation of each facility type. $K_{G,T}$ and $X_{G,T,DAY,HR}$ are the capacity and output of power resource respectively and N_{DAY} the numbers of the day of each representative daily load curve.

Major constraints accounted in the model are:

- Capacity balance of each facility type (existing and newly constructed)
- Demand and supply balance in each time of day
- Constraint of reserve margin
- Planned outage of each facility type
- Load following capability of each facility type
- Storage and generation balance of pumped hydro
- Other limitations (fuel consumption, construction of power plants, and/or CO_2 emission)

5. Presuppositions about PEM-FC cogeneration system

Technical conditions of a PEM-FC system are shown in Table 2. Values in the standard case are targets at the practical use in near future based on the Nikkei Mechanical [5]. Also, some technical progress is assumed in the advanced case. In this case, both of purchased electricity and town gas will decrease because of improved generating efficiency and heat recovery. For about the operating pattern of a PEM-FC system, daily start and stop (DSS) operation is assumed, considering the tank capacity of hot water. A typical pattern of demand and supply of hot water is shown in Fig. 3.

I estimated the cumulative capacity stock of PEM-FC systems toward 2020 as shown in Fig. 4. This estimation is done mainly from the numbers of newly constructed detached house in which FC systems can be most economically introduced. Higher value is almost close to the target of the government and lower value is just one third of higher value. In the high case, 13.5 million units of PEM-FC systems will penetrate until 2020, and it means PEM-FC systems will be introduced almost all newly constructed detached house.

Table 2. Technological specification of the PEM-FC system

	Standard case	Advanced case
Unit capacity	0.7 kW	
Fuel	Town gas, Propane gas	
Generating efficiency	30.9% (LHV)	35.0% (LHV)
Overall efficiency	62.6% (LHV)	70.0% (LHV)
(Energy consumption of house)		
w/o PEM-FC system: Electricity	5,109 kWh/year	
: Town gas	431 m^3/year	
with PEM-FC system: Electricity	816 kWh/year	695 kWh/year
: Town gas	1,197 m^3/year	1,086 m^3/year
Operating pattern	Operation between am7-am0, daily start and stop	

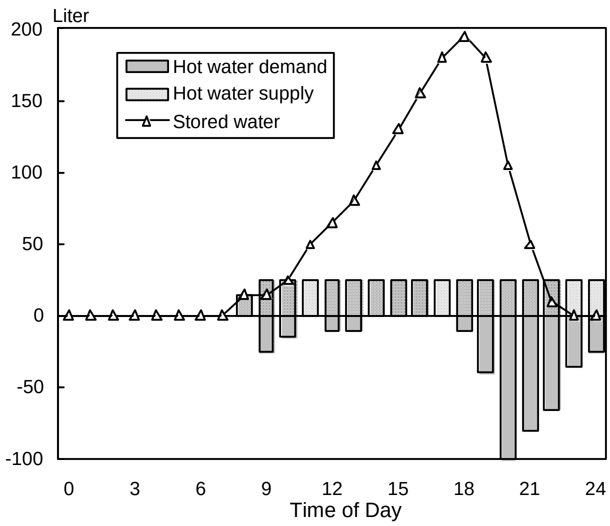

Fig. 3. Example of the demand and supply of hot water and stored amounts

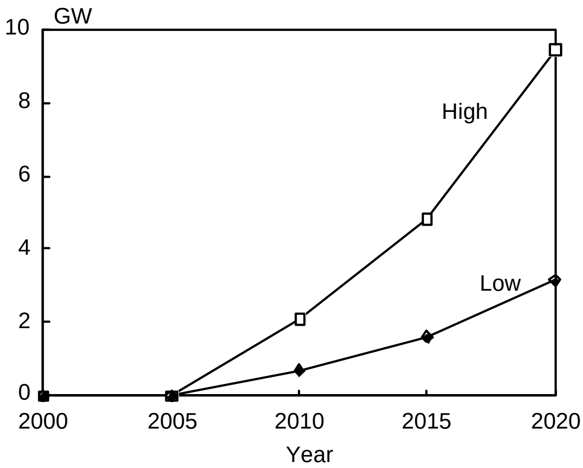

Fig. 4. Assumptions of the penetrated capacity of the PEM-FC systems

6. Presuppositions about electric utility

Future electricity demand in Japan until 2020 is shown in Table 3. This value is based on the estimation by electric utility until 2011 in March 2002 and saturation is assumed because of the slowdown of economic growth by population decrease after that. Fuel prices are estimated as in

Table 4, based on the actual record in 2000 and outlook by the government. Moreover, planned changes in energy taxes shown in Table 5 are accounted in all cases. With this change, total amounts of tax revenue for electric utility will not change. However, coal price will rise more than 10% and the competitiveness of coal power will decrease. Discount rate and reserve margin are set to be 3% and 10% respectively.

Table 3. Estimates of average growth rate of electricity demand

Period	2000-2005	2005-2010	2010-2015	2015-2020
Annual kWh	0.85%	1.75%	1.0%	0.5%
Peak demand	0.85%	1.75%	1.0%	0.5%

Table 4. Estimates of fuel prices (real price in 2000)

Fuel type / year	2000	2005	2010	2015	2020
Nuclear (yen/kWh)	1.58	1.58 (0.0%)	1.58 (0.0%)	1.58 (0.0%)	1.58 (0.0%)
Coal (yen/kg)	4.73	4.31 (-1.8%)	4.58 (1.2%)	5.74 (4.6%)	7.06 (4.2%)
LNG (yen/kg)	28.91	29.50 (0.4%)	32.83 (2.2%)	41.28 (2.3%)	45.89 (2.3%)
Crude oil (yen/*l*)	25.99	27.50 (1.1%)	31.26 (2.6%)	35.82 (2.8%)	40.93 (2.7%)
C heavy oil (yen/*l*)	25.59	26.83 (1.0%)	30.10 (2.3%)	34.04 (2.5%)	38.42 (2.5%)

Note: Values in parentheses mean annual average growth rates.

Table 5. Planned changes in the rates of energy taxes

	Crude oil	LNG	LPG	Coal	Electricity
Current rates	2040 yen/k*l*	720 yen/t	670 yen/t	-	0.445 yen/kWh
Planned rates					
2003.10-2005.3	No change	840 yen/t	800 yen/t	230 yen/t	0.425 yen/kWh
2005.4-2007.3		960	940	460	0.400
2007.4-		1080	1080	700	0.375

Table 6 shows the economic and technical conditions of new power plants. Among these values, generating efficiency of advanced LNG combined cycle (to be called LNG-CC hereafter) is important because technical progress of LNG-CC is remarkable recently and CO_2 emission factor of it is extremely small. Generating efficiency of most advanced LNG-CC in reaches 53% and 50% is adopted in this study. CO_2 emission factor is about 100 g-C/kWh and it is less than half of coal power plant. It means if advanced LNG-CC will be introduced in the base scenario and its construction will be postponed by the penetration of PEM-FC systems, avoided CO_2 emission from electric utility would be quite limited.

As for new construction of nuclear power plant and pumped hydro, taking the severe site constraint into account sets up upper limits. An upper limit is also imposed for CO_2 emission in 2010, considering the Keidanren Voluntary Action Plan on the Environment. CO_2 emission factor of electric utility in 2010 should be decreased below 80% level in 1990.

Combining these presuppositions, ten cases are simulated in total. Table 7 shows the settings of each case. Case 0 and Case n are the reference cases in which PEM-FC system is not introduced. The result of Case 0 should be compared with those of Case LS, Case HS, Case LA, and Case HA. And the result of Case n should be compared with those of Case LSn, Case HSn, Case LAn, and Case HAn respectively.

Table 6. Estimates of various conditions of new power plants

	Nuclear	Coal	LNG-CC (Conventional)	LNG-CC (Advanced)	Oil	Pumped hydro
Construction cost (Thousand yen/kWh)	338	308	208	208	287	196
Operating cost (yen/kWh)	1.81	1.40	1.08	1.08	1.43	0.00
Annual rate of expenditure	9.09%	9.05%	9.05%	9.05%	9.05%	5.14%
Durable time (years)	40	40	40	40	40	50
Generating (storage) efficiency	-	40%	46%	50%	37.5%	65%
Plant use rate	4.5%	7.0%	3.0%	2.0%	5.0%	0.5%
Used fuel	-	Coal	LNG	LNG	Crude oil: 40% Heavy oil: 60%	-
Upper limit of utilization (Annual average)	80%	65%	83%	83%	79%	-
Upper limit of construction between 2000-2010 (GW)	12.63 (10 units)	15.65	No limit	No limit	No limit	2.70
Upper limit of construction after 2010 (GW/year)	1.2	No limit	No limit	No limit	No limit	0.60

Table 7. Case Settings

Case	0	LS	HS	LA	HA	n	LSn	HSn	LAn	HAn
Diffusion rate of FC	No	Low	High	Low	High	No	Low	High	Low	High
Efficiency of PEM-FC	-	Standard	Standard	Advanced	Advanced	-	Standard	Standard	Advanced	Advanced
Nuclear construction	10 units between 2000-2010 + 1.2 GW/year					4 units (under construction) only				

7. Results

7.1 Without PEM-FC systems

Fig. 5 and Fig. 6 shows the capacity and generated power of power plant by plant type in Case 0. In this scenario, coal and advanced LNG-CC will increase their capacity and generated power in future. Nuclear power is still competitive, however, its capacity and generated power will turn to decrease after 2015. This is because upper limit of construction exists and a lot of existing capacity will fulfill their lifetime.

In Case n, where the upper limit of newly constructed nuclear power will be severer, the dependence on fossil power plants should increase. Fig. 7 compares the capacity of new power plants between Case 0 and Case n. Between 2005-10, advanced LNG-CC will be introduced in place of nuclear and coal power. But after 2010, coal power will be subsisting for nuclear and LNG-CC power. This is because the increasing rate of coal price is smaller than LNG until 2015 and the competitiveness of coal power will get stronger against LNG-CC power, even if the energy tax rates will be changed unfavorably for coal.

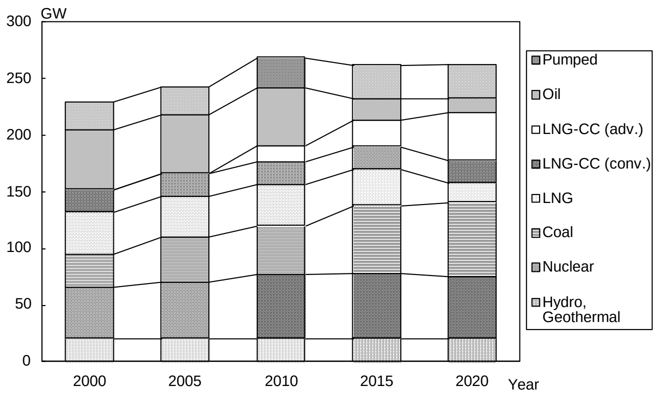

Fig. 5 Capacity of power plant by type (Case 0)

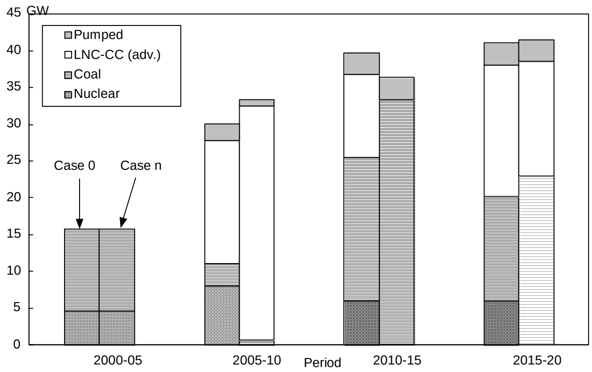

Fig. 7 Capacity of new power plant by type (Case 0 and Case n)

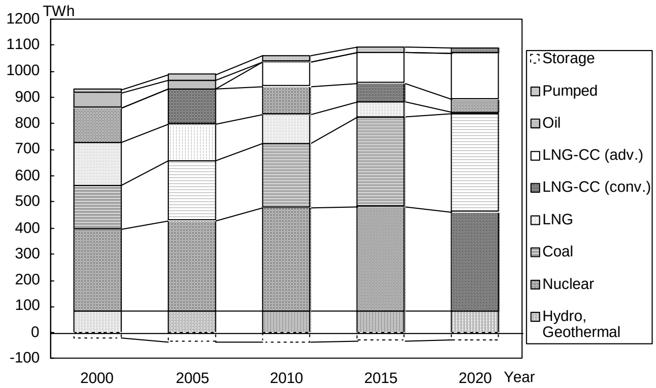

Fig. 6 Generated power of power plant by type (Case 0)

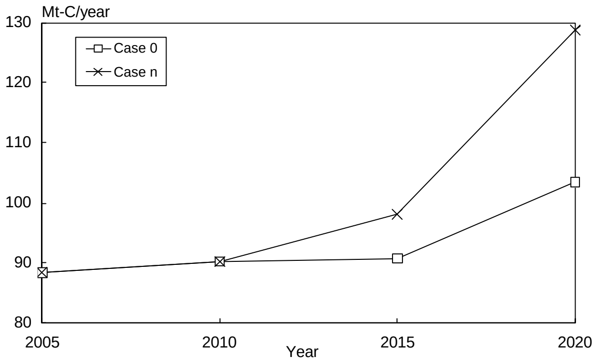

Fig. 8 CO_2 emission (Case 0 and Case n)

These dynamic changes in power generation mix affect CO_2 emission from electric utility seriously. Fig. 8 compares total CO_2 emission from electric utility. The reason why CO_2 emission in 2010 is equal is that an upper limit is imposed as described before. In Case 0, CO_2 emission remains stable until 2015, but it will increase after that because total capacity and generated power of nuclear power will decrease. In Case n, the increase in CO_2 emission becomes greater. CO_2 emission in 2015 and 2020 in Case n are 25% and 32% larger than Case 0 respectively. These differences in CO_2 emission will have an influence on avoided CO_2 emission from electric utility by introducing PEM-FC systems in the next paragraph.

7.2 With PEM-FC systems

Fig. 9 shows the changes in the capacity of electric utility by plant type in 2020 according to demand decrease by the penetration of PEM-FC systems. An interesting difference can be seen concerning nuclear development in the reference cases. If nuclear power will be developed constantly, both coal and LNG-CC power will decrease. On the other hand, if the development will be limited to the plants under construction only, coal power will increase and LNG-CC power will decrease more. As a result, decreases in CO_2 emission in the former cases are larger than the latter cases especially in 2020 (see Fig. 10).

The emission factor of avoided CO_2 emission by reduced electricity demand has often been argued in Japan. A most typical manner is to adopt the averages of total power plants and/or of thermal power plants only. The basis using latter idea is that CO_2-free power plants such as nuclear and hydro power will not change their output because of two reasons; variable costs are very cheap and they cannot change their output technically. This idea is appropriate in the short term. But in the long term, dynamic changes in power generation mix should be considered.

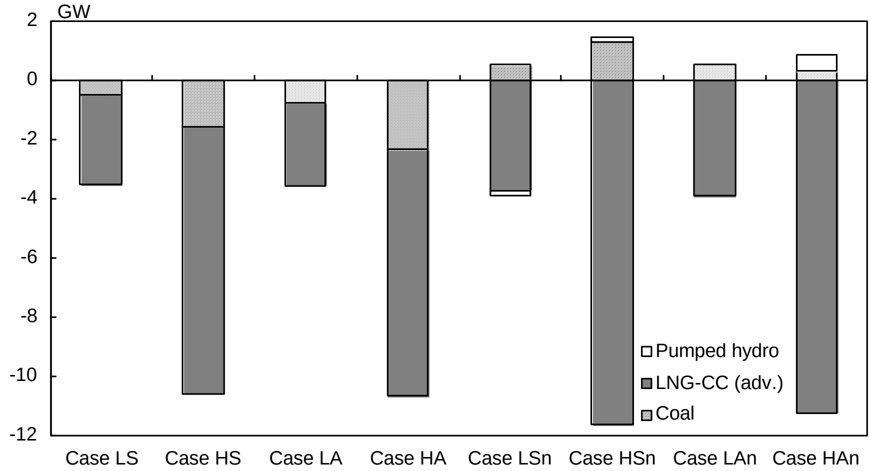

Fig. 9. Changes in capacity of electric utility by plant type compared with the reference cases (in 2020)

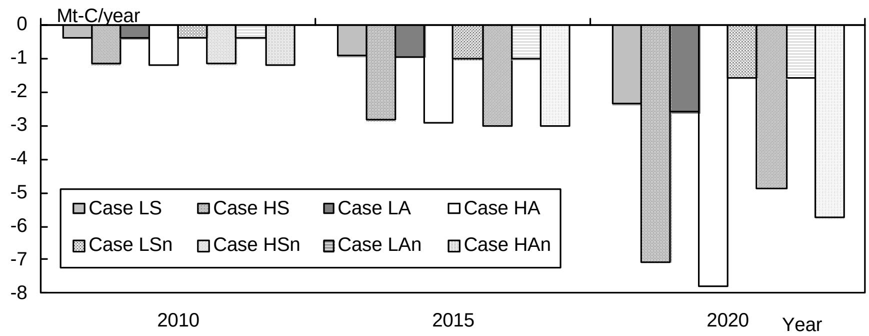

Fig. 10. Changes in CO_2 emission from electric utility compared with the reference cases

The emission factor of avoided CO_2 emission by introducing PEM-FC systems can be illustrated as in Fig. 11. Whether nuclear power will be developed constantly or not, the emission factors are close to total average in the reference cases. It means the former idea is approximately right in this case. But if the presupposition about operating pattern of PEM-FC systems will change (for example, whole day continuous operation), the result might change.

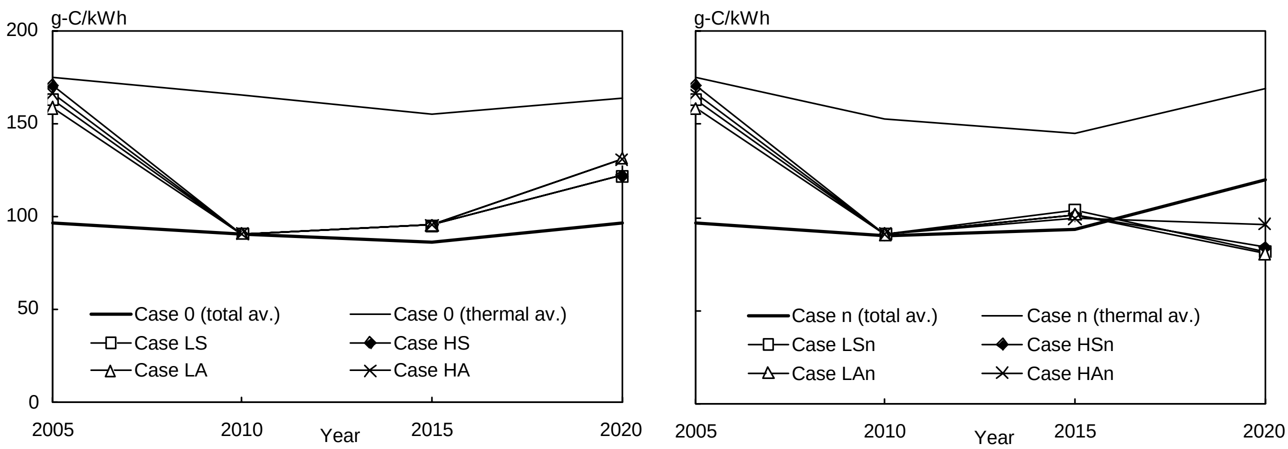

Fig. 11. Average emission factor of avoided CO_2 emission from electric utility

7.3 Total change in CO_2 emission

Table 8 shows CO_2 emission from PEM-FC systems. They are simply calculated by multiplying cumulative numbers of a PEM-FC system, fuel consumption per unit, and a CO_2 emission factor of each fuel. For stationary PEM-FC systems, town gas (mostly methane) is the most promising fuel. However, more than half of newly constructed detached house locates the area where town gas is not supplied. So 50:50 mixture of town gas and propane gas is considered additionally in this study. C/H ratio of propane is larger than methane and the reformer of propane is less efficient than methane. Moreover, CO_2 emission factor of propane is larger than methane. As a result, I assume CO_2 emission of PEM-FC systems using propane is 20% larger than that of methane systems.

By combining CO_2 emissions from electric utility and from PEM-FC systems, total changes in CO_2 emission is shown in Fig. 12. Whether overall emission will decrease or increase depends on scenarios such as the development of nuclear power and technical progress in efficiencies of PEM-FC systems.

Table 8. Changes in CO_2 emission from PEM-FC systems

(Thousand t-C/year)

	2000-2005	2005-2010	2010-2015	2015-2020
100% town gas				
Case LS	0.5	492	1,132	2,215
Case HS	1.5	1,476	3,396	6,644
Case LA	0.4	421	967	1,893
Case HA	1.3	1,262	2,902	5,678
50% town gas, 50% propane gas				
Case LS	0.5	541	1,245	2,436
Case HS	1.6	1,624	3,735	7,308
Case LA	0.5	463	1,064	2,082
Case HA	1.4	1,388	3,192	6,246

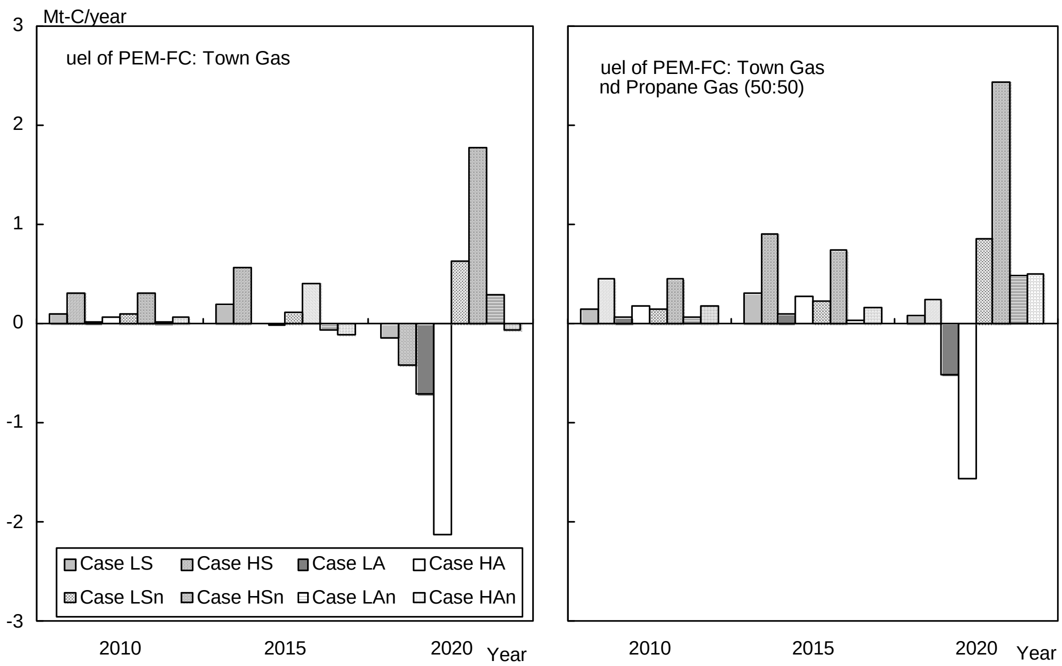

Fig. 12. Changes in CO_2 emission (electric utility and PEM-FC, compared with the reference cases)

Table 9. CO_2 emission per household

(kg-C/household/year)

Year / Case	Case LS	Case HS	Case LA	Case HA	Case LSn	Case HSn	Case LAn	Case HAn
Fuel of PEM-FC: 100% town gas								
2015	828.3 (+11.0%)	827.9 (+11.0%)	744.9 (- 0.1%)	744.4 (- 0.2%)	830.1 (+ 5.9%)	842.2 (+ 7.5%)	756.4 (- 3.5%)	766.5 (- 2.2%)
2020	765.9 (- 4.0%)	766.8 (- 3.9%)	640.0 (-19.8%)	640.9 (-19.7%)	1,067.4 (+15.3%)	1,057.6 (+14.2%)	990.5 (+7.0%)	920.9 (- 0.5%)
Fuel of PEM-FC: 50% town gas, 50% propane gas								
2015	905.2 (+17.0%)	904.8 (+17.0%)	814.7 (+ 5.3%)	814.1 (+ 5.2%)	907.0 (+11.8%)	919.1 (+13.3%)	826.2 (+ 1.8%)	836.2 (+ 3.0%)
2020	842.8 (+ 2.0%)	843.7 (+ 2.2%)	709.7 (-14.1%)	710.7 (-14.0%)	1,144.3 (+20.0%)	1,134.5 (+19.0%)	1,060.3 (+11.2%)	990.6 (+ 3.9%)

Note: Values in parentheses mean the deviation rates from the reference cases.

CO_2 emission per household is shown in Table 9. In the largest case, CO_2 emission will decrease by 20% in 2020. On the other hand, 20% increase can be seen in the worst case. Thus, the changes in CO_2 emission per household distribute from -20% to +20%. This result is quite different from other quantitative analyses in which a static power generation mix is only considered.

8. Conclusions

This study analyzed the dynamic changes in power generation mix and CO_2 emission by introducing PEM-FC stationary cogeneration systems in Japan toward 2020. The results are summarized as follows:

- LNG-CC power will mainly decrease by introducing of PEM-FC systems. Because LNG-CC power is quite efficient, the emission factor of avoided CO_2 emissions from electric utility will be limited. They are close to the emission factor of total average in the reference cases where PEM-FC systems are not introduced.
- It is not observed that overall CO_2 emissions including the emissions from PEM-FC systems will always decrease. In particular, CO_2 emissions will clearly increase if the development of nuclear power will be limited and technical progress in efficiencies of PEM-FC systems will not be achieved in future.

The results of this study are quite meaningful. It suggests that dynamic changes in power generation mix are important to analyze the changes in CO_2 emission from electric utility. Also it appeals that PEM-FC systems do not always contribute to mitigate CO_2 emission, even if technical progress in efficiencies of PEM-FC systems will be achieved.

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