Fundamental Studies on Penetration of Fuel Cells and Energy Transfer in Japan

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Abstract— **On-site Distributed Generations (DG), which are installed into energy consumers, are spreading. Energy networks should evolve to deal with future state that considerable numbers of on-site DGs including fuel cell (FC) are involved to the networks. DGs are considered to be uses as combined heat and power systems (CHP) in Japan.**

Fundamental studies on energy networks which involve on-site DG (Distributed Generation) in residential dwellings were performed in this paper. Outlines of future energy networks which involve on-site DGs are described with concept drawings and some items which should be considered. Two case studies on penetration of FCs into residential dwellings and the effect of energy transfer were performed. The case studies considered mitigation of environmental impact and reduction of economic impact.

One of the case studies assumes a small apartment building. Some or all of the dwellings install FCs. The energy network employs energy transfer among the dwellings. A group of 10 residential houses is assumed in the other case study. The houses are assumed to install FCs and make use of energy transfer.

The result of those studies revealed that employment of energy transfer increases the introduction effect and encourages rapid penetration of FCs especially in early stage of the penetration. The rapid penetration of FCs realizes the reduction of environmental impact and energy cost in next some decades.

I. INTRODUCTION

On-site distributed generations (DG), which are installed into energy consumers such as photovoltaic module (PV), combined heat and power system (CHP), are increasing. That tendency is expected to be accelerated by development of new type of DGs such as fuel cell (FC) and de-regulation of energy business.

The penetration of micro-DGs into small-scale consumer including residential dwellings or drug stores shall influence existing power systems and distribution grids. Electricity companies are urged to change their business styles in Japan. On the other hand, consumers are expected to concern more about their electricity supply and demand, because they are involved to electricity markets not only as consumers but also as suppliers.

Influences on upper systems will not be negligible, when a number of DGs are operated disorderly by consumers. Reliability and quality of electricity could be damaged [1].

DGs contribute to mitigation of environmental impact, because they are usually operated as CHP in Japan. Operation as CHP increases their total efficiencies, because not only electricity but also heat, which is by-product of generation, is gained. However, it is doubtful that small-scale consumers are able to fully exploit both electricity and heat.

Appropriate operation and control of DGs should be considered to deal with the state that considerable numbers of DGs are introduced to small-scale consumers. Application of centralized control system is far from reasonable measure.

Not independent operations of DGs of each consumer, but cooperative operation of the DGs of some consumers is effective to make use of both electricity and heat, if CHPs such as FCs or gas engines are installed as DGs.

The cooperative operation requires new type of energy networks which transfer energy among consumers efficiently. To add electricity other energy devices such as hot water are considered in urban areas, where are crowded with many apartment buildings and residential houses in Japan.

Authors carry out researches into optimum energy networks considering mitigation of environmental impact without giving any disadvantages to the consumers such as reliability and quality of electricity and economic impact [3].

Analyses on the effect of energy transfer, environmental impact, consumers' economic impact and the penetration of DGs were performed and are described in this paper.

As the result, the paper provides that energy transfer greatly contributes to the rapid penetration of FCs in early stage of the penetration and reduction of environmental impact and energy cost in next some decades.

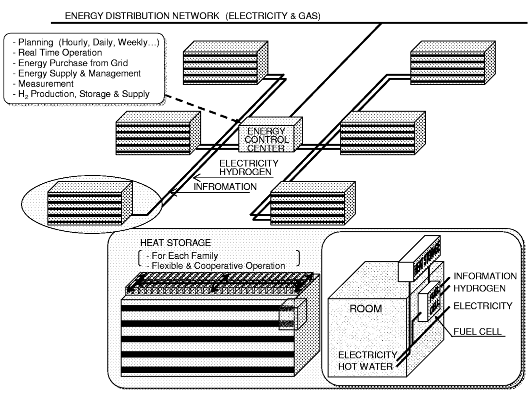
II. ENERGY NETWORKS

The scope of energy networks are variously considered from large-scale (city, village) to small-scale (combination of a few houses). Concept drawings are shown in Fig. 1. Those drawings are only a few examples. Many other variations are considerable.

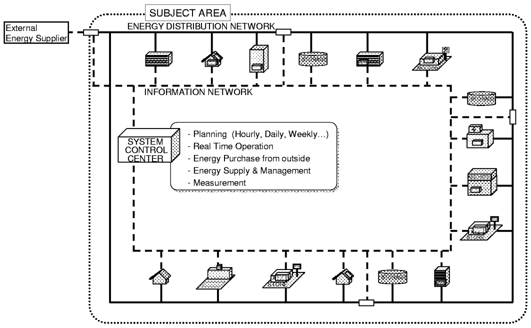
CHP is considered mainly as DG system. The DGs and energy storage equipment are installed appropriately on the energy networks. Energy is transferred from a consumer to other consumers via the networks. Electricity, gas and hot water (or steam) are considered as energy devices. Use of hydrogen is also considered in near future. Information technology is applied to operations of equipment such as DGs and energy storage, and monitoring and controls of the networks.

Following items should be considered.

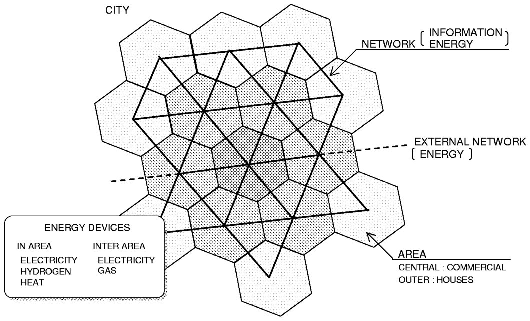
- Scale of the energy networks
- Characteristics of involved consumers
- Energy devices and their maximum distance of transfer



(a) Example for Residential Houses



(b) Example for Small Areas



(c) Example for Cities, Wards

Fig. 1. Concept of Energy Networks

- Devices, characteristic and cost of energy storage
- Thorough use of both electricity and heat
- Fairness of operational strategy and objective function
- Consistency with conventional energy networks
- Technological issues such as reliability and quality of distribution grids

III. CASE STUDY I (AN APARTMENT BUILDING) [3]

A case study for an apartment building which consists of 10 dwellings was performed. It can be considered as a smaller case of Fig. 1(a). Bottom up simulations were performed by linear programming models.

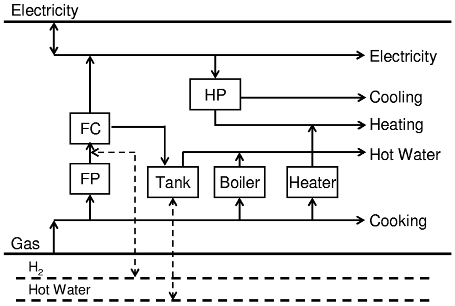


Fig. 2. Configuration of Dwellings

A. Assumption

FCs are assumed to be installed into some or all of the dwellings. Three scenarios were assumed for comparison; (i) energy transfer is available among consumers, (ii) only electricity can be transferred, (iii) any energy transfer is unavailable.

Electricity and gas were supplied from outside. The apartment building contracts those energy suppliers as a single consumer. Energy control center (ECC) is located in the apartment building for the management of energy purchase from the outside, internal energy transfer and operation of the FCs.

Energy system configuration of the dwelling is shown in Fig. 2. To add to electricity and gas hydrogen distribution pipes are installed. Hot water storages of each dwelling can be installed on the top of the apartment building and interconnected for energy transfer each other. If a dwelling installs a FC, the FC is installed to the house and a water storage is installed on the top of the apartment building.

Dwellings which have FCs use fuel processor to make hydrogen from gas and operate their FCs. They can consume generated electricity by themselves and can back to internal grid of the apartment building. It is not economical to sell to the electricity company, because the price of backward flow is very low in Japan. Backward flow from the dwellings should be transferred to other dwellings and consumed in the apartment building.

Heat of the FCs is recovered as hot water. The hot water is stored in the hot water storage on the top. The dwellings also can consume the hot water by themselves and can transfer to other dwellings.

Parameters used in this case study are shown in Table I. Energy demand of the dwellings (3 seasons, 24 hours per day) is assumed by random numbers based on the data described in [2]. Table II shows average of annual demand.

B. Calculation Result

Result of load factor (Fig. 3) clearly represents that energy transfer increases operation of FCs (load factor) and introduction effect of FCs. FCs supplies 57% of electricity demand, when the FCs are installed to five dwellings in Case (i). It increases to 96%, as all of the dwellings have FCs.

Fig. 4 illustrates electricity purchase, when five dwellings have FCs in Case (i). Black line shows the purchase of the

TABLE I
SETTINGS

Item		Value	
Efficiency / COP			
FC(PEFC)	(Gen.)	43.75	%
	(Heat)	50	%
FP		80	%
Boiler		80	%
Loss			
Tank	(I/O)	1	%
	(Stock)	1	%/h
H_2	(I/O)	1	%
Electricity trans.		0.5	%
H_2 trans.		1.0	%
Hot Water trans.		2.0	%
Energy Price			
Electricity	(Buy)	26.82	yen/kWh
	(Sell)	8.94	yen/kWh
Gas		130.0	yen/Nm^3
CO_2 Emission Intensity			
Electricity	(day-time)	97.1	C-g/kWh
	(night-time)	72.8	C-g/kWh
Gas		0.0575	C-g/kcal
Other constants			
Electricity	→ P. Energy	2250	kcal/kWh
	→ S. Energy	860	kcal/kWh
Gas	→ P. Energy	11,000	kcal/Nm^3
Hot Water	→ P. Energy	60.0	kcal/`
H_2	→ P. Energy	3034.3	kcal/Nm^3
Capacity			
FC		1.0	kW
Boiler		42	kW

FC: Fuel Cell, FP: Fuel Processor
P. Energy: Primary Energy
S. Energy: Secondary Energy

TABLE II
ANNUAL DEMAND (AVERAGE)

Unit = Mcal

Electricity	Cooling	Heating	Water Heating	Cooking
2,055	311	2,261	2,017	738

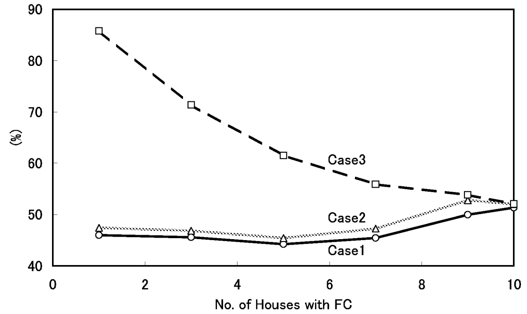


Fig. 3. Load Factor of FC

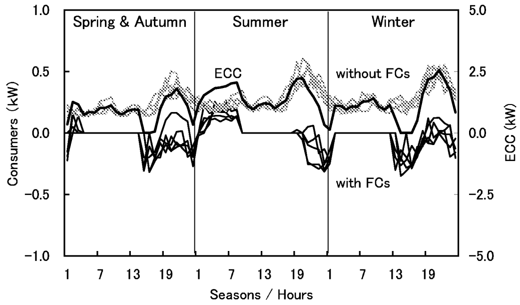


Fig. 4. Electricity Buy (5 of 10 have FC)

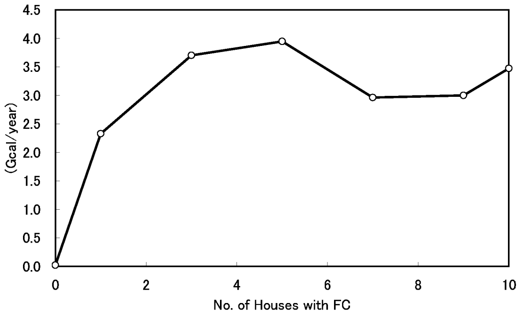


Fig. 5. Hot Water Transfer

dwellings with FCs and gray lines shows the purchase of the dwellings without FCs. Thick line indicates the purchase of the ECC from the outside.

The electricity is transferred from the dwellings with FCs to the dwellings without FCs, and no backward flow from the ECC to commercial grids is found in the result (Fig. 4). The dwellings with FCs purchase only little electricity without summer season. Electricity which is generated by the FCs to cover their hot water demand at night-time is transferred to other dwellings.

Fig. 5 shows annual transfer of hot water among the dwellings. The transfer increases as the number of dwellings with FCs increases, when less than three dwellings have FCs. The transfer reaches to approximately 4 Gcal/year when five dwellings have FCs. It equals approximately 20% of total demand of all the dwellings, and indicates that the energy transfer system works actively.

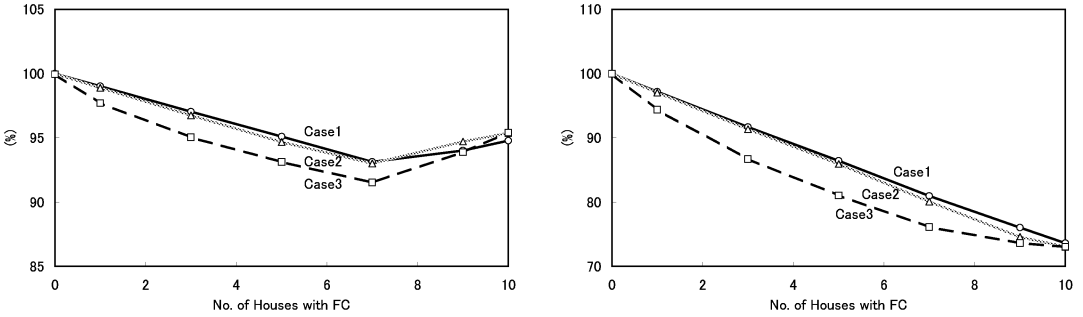
Fig. 6 illustrates the calculation results on evaluation indexes.

CO_2 emission (Fig. 6(a)) is reduced to a minimum, when 7 dwellings have FCs. The reason why CO_2 emission becomes larger when the number of dwellings with FCs is larger than 7 is characteristics of the dwellings and their combination.

Case (i) has advantages in primary energy consumption (Fig. 6(b)) and annual energy cost (Fig. 6(c)) comparing with Case (iii). The difference becomes smaller, as the number of dwellings with FCs increases.

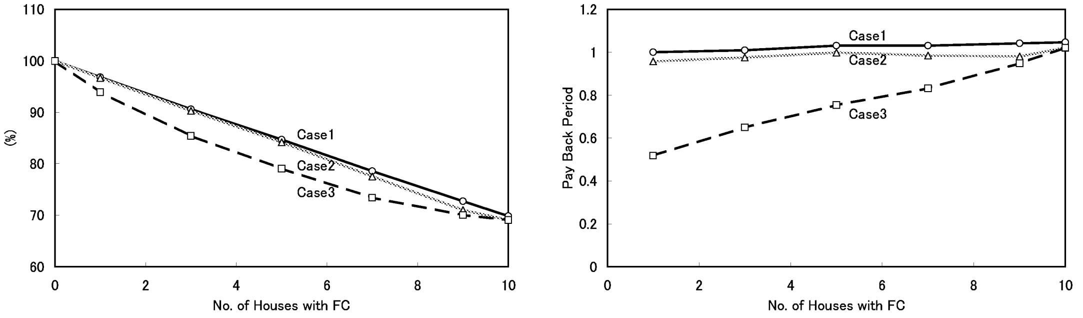
Reduction effect of above three indexes of Case (i) is 1.2–1.5 times of those of Case (iii). However the effect becomes smaller as the increase of the number of dwellings with FCs.

Comparison among pay back period of each case is shown in Fig. 6(d). The pay back period is obtained by dividing cost of the FCs, the hot water tanks and other equipment by reduction of energy cost (Fig. 6(c)). The value is divided also by the value of that no dwellings has FCs in Case (iii). For



(a) CO_2 Emission

(b) Primary Energy



(c) Energy Cost

(d) Pay Back Period

Fig. 6. Evaluation Indexes

example, when five dwellings have FCs, the value of Case (iii) is 1.0 and that of Case (i) is 0.75. It shows that the pay back period is reduced to 75% by introduction of energy transfer.

The pay back period is almost constant in Case (iii) without regard to how many dwellings have FCs, because the dwellings are independent each other on energy supply and demand. Effective operation by the use of energy transfer reduces the pay back period in Case (i).

The analyses on above indexes provide that energy transfer encourages the introduction effects of FCs especially when a few FCs are introduced. On the other hand, there is no clear difference can be found among three cases when many dwellings have FCs. Therefore, the use of energy transfer provides great effects in promotion stage of FCs.

IV. CASE STUDY II
(A GROUP OF RESIDENTIAL HOUSES) [4]

An analysis on progress of penetration of FCs into a group which consists of 10 residential houses was performed. The calculation period is 30 years. The prices of FC systems are assumed to fall year by year. The analysis was performed from the point of view of influences of energy transfer on evaluation indexes such as cost for houses and environmental impact.

Two scenarios were assumed for comparison; (i) energy transfer is available among houses, (ii) any energy transfer is unavailable.

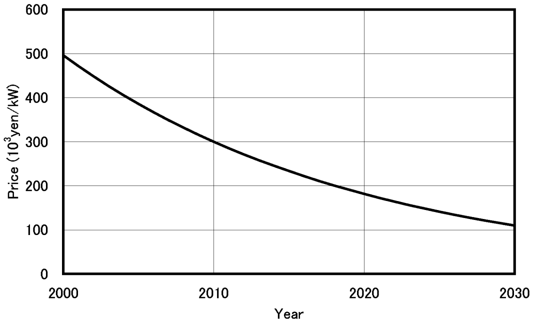


Fig. 7. Price of FC

A. Assumption

An experience curve was applied to assume the price of a FC. The price was shown in Fig. 7.

(1) The progress ratio was assumed to be 80%, while the ratio of photovoltaic modules on the world market is 82% [5].
(2) The cumulative installed capacity was assumed to be 210 MW in 2010 and 1,000 MW in 2020 [6]. Its rate of expansion was assumed to be constant.
(3) The price in 2010 is assumed to be 300,000 yen/kW [6].

A group which consists of 10 residential houses is assumed as shown in Fig. 8. A house which has a FC is able to transfer energy to next houses.

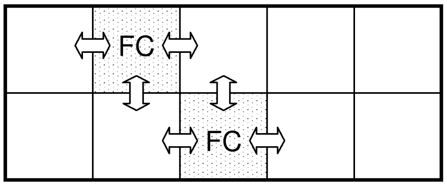


Fig. 8. A group of Residential Houses

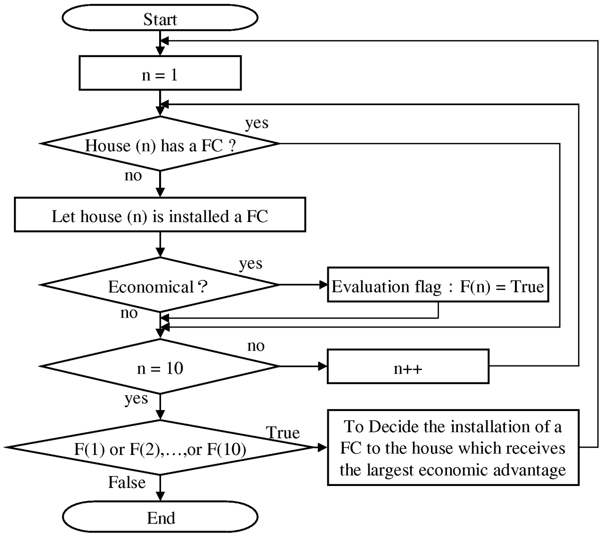


Fig. 9. Algorithm for decision making of installation of FCs

Energy demand of the households (3 seasons, 24 hours per day) is assumed by random numbers as same as III. However assumed data is different.

Assumed parameters of this study are almost same as III (Table I).

Regarding to a fuel processor, frequent start and stop, and lower operation should be avoided as much as possible, because the fuel processor needs preheat before operation and its efficiency drops remarkably as its output decreases. Those characteristics are built in a model (mix-integer) in this study. One hour preheat is assumed to be needed to the fuel processor.

Gas boilers (water heaters) and hot water tanks are assumed to be installed to all the houses whether they have FCs or not. Houses which install FCs install complete FC systems (FCs, hydrogen tanks and other miscellaneous equipment).

The FCs are assumed to require maintenances every year and an overhaul five years after installation. Life spans of the FC systems are assumed to be 10 years. Purchase and reinstallation of a new FC system is necessary after that.

An algorithm for decision making of the installation of the FCs is shown in Fig. 9.

The objective function is minimization of the cost for the group of houses. Economic advantage for the group when a FC is installed to one of the house is calculated for every house.

The reduced cost for energy purchase by the introduction of a FC is compared with the cost for the FC system (equipment cost, maintenance cost and overhaul cost) in the life span of the FC system (10 years). The difference of those two values is considered to the economic advantage (or disadvantage). The introduction of the FC systems is considered to be economical, if the former is larger than the later.

No FC system will be installed in a year, if the result of above calculation shows that introductions of FC systems are not economical for all of the houses in the year; the prices of the FC systems are assumed to fall year by year as has been mentioned. A FC system is decided to be installed to a house, if only the introduction of a FC system to the house is economical. If more than one house which will receive economic advantages by the introductions of FC systems is found, a FC system is decided to be installed to the house which receives the largest advantage. Calculations to check if additional introduction of FC systems to other houses will be performed after the decision. As the result, a combination of houses which receives a maximum economic advantage by installations of FC systems is obtained.

B. Calculation Result

FCs are introduced as shown in Fig. 10. Numbers in the boxes show when the FCs are introduced to the houses (first year = 0, E = 30th year).

Comparison of the two cases reveals that the introduction of FCs begins from earlier year by the employment of energy transfer.

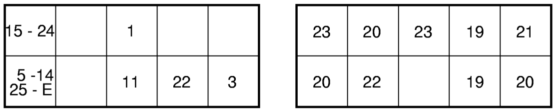
The decision making which house a FC should be installed greatly depends on whether energy transfer is available from the house to next houses or not. A tendency appears in Fig. 10(a) that FCs are introduced to the houses which are not next to houses which already have FCs.

The economic indexes are illustrated in Fig. 11.

The cost reduction begins at earlier year in Case (i) comparing with Case (ii), because the introduction of FCs begins earlier. The introduction of FCs in earlier year costs larger for equipment, but it will be recovered by the reduction of cost for energy in future.

FCs are introduced to three houses in Case (i) by 10th year, while no FCs are introduced in Case (ii). The reduced cost in Case (i) at that time almost equals to that of Case (ii) when 6 (21st year) or 7 (22nd year) houses are installed FCs.

The cost for energy in Case (i) is smaller than in Case (ii) in 28th and 29th years, though FCs are installed to only 5 houses in Case (i) while 9 FCs are introduced in Case (ii). Thus, energy transfer encourages economic effect of introduction of FCs even if only a few FCs are introduced.



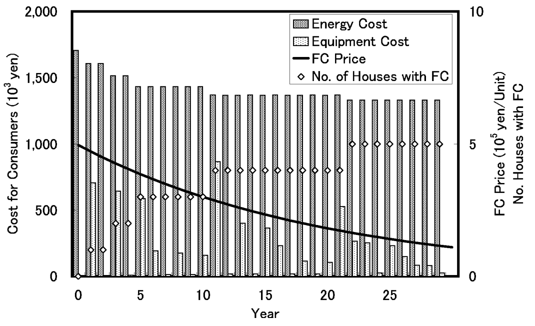
15 - 24		1		
5 -14 25 - E		11	22	3

(a) Case (i)

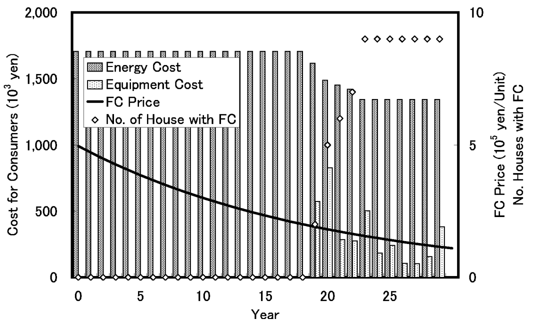
23	20	23	19	21
20	22		19	20

(b) Case (ii)

Fig. 10. Installation of FCs



(a) Case (i)



(b) Case (ii)

Fig. 11. Economic Indexes

Primary energy consumption and CO_2 emission are also considered evaluation indexes and shown in Fig. 12.

There is no clear difference between Case (i) and Case (ii) on annual reductions of those indexes when quiet a few FCs are introduced (28th year or later). However, the reductions of indexes begin early in Case (i), because the introduction of FCs begins earlier years. The cumulative reduction rate[1]of Case (i) is 2–3 times larger than that of Case (ii) in 28th year.

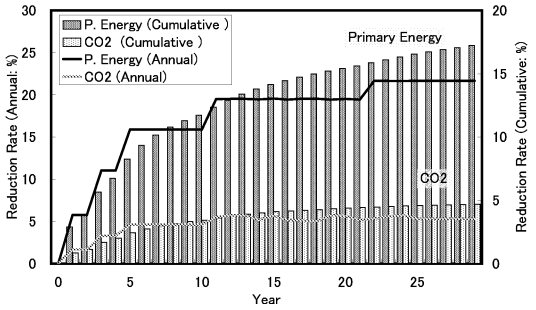
The introduction of FCs in earlier stage, which is encouraged by employment of energy transfer, provides mitigation of environmental impact in next a few decades.

The progress of FC introduction depends on effectiveness of the energy transfer in Case (i). Annual energy transfer reaches the peak when four houses have FCs. Cost efficiency falls, if more FCs are introduced. Approximately one thirds of the annual hot water demand is transferred at the maximum.

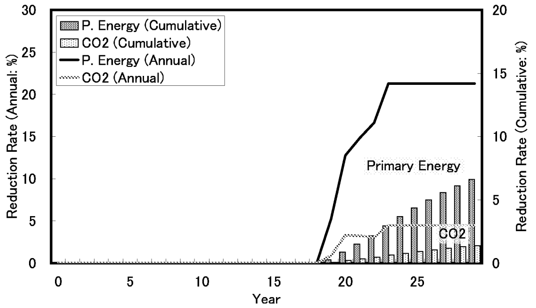
V. CONCLUSION

Energy networks which improve the introduction effect of DGs and optimize throughout systems in conditions where the introduction of on-site DGs becomes popular are described in this paper. Two kinds of case studies on cooperative operation of FCs and energy transfer among consumers were performed as fundamental studies of the energy networks.

The conclusions reached from the case studies are as follows.



(a) Case (i)



(b) Case (ii)

Fig. 12. Environmental Indexes

(1) The employment of energy transfer encourages the effect of FCs especially in early stage of the penetration.
(2) The rapid penetration of FCs realizes the reductions of energy cost and environmental impact in next some decades.
(3) Equal effects on the reductions of energy cost and environmental impact are obtained with fewer FCs if the energy transfer is employed.

Further consideration from electrical technical view and more analyses to reveal characteristics and effects of the cooperative operation of DGs and the energy transfer will be performed at the next stage of this study.

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[6] Fuel Cell Project Team, Senior Vice–Minister Meeting "Report of Fuel Cell Project Team" (in Japanese) May 2002

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[1] xth year: $\sum_{year=0}^{x} \frac{\text{Index Value without FCs(year)} - \text{Index Value(year)}}{\text{Index Value without FCs(year)}}$