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Economic and Environmental Effects of Installing Distributed Energy Resources into a Household

Akito Ozawa*, Yoshikuni Yoshida

Department of Environment Systems, Graduate School of Frontier Sciences, The University of Tokyo, Tokyo, Japan
Email: *ozawa@globalenv.k.u-tokyo.ac.jp

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Abstract

Improving energy efficiency in the residential sector is a pressing issue in Japan. This study examines the economic and environmental impacts of introducing the following distributed energy resources: photovoltaics (PV), a fuel cell, and a battery. We estimate electricity and hot water demand profiles of a household by using simulated living activities. Electric power from a residential PV system is also calculated from the observed solar radiation. By using mixed integer programming, we perform a cost minimization operating simulation of a residential PV, fuel cell, and battery. The result suggests that we can create a net-zero energy house by installing both a PV system and a fuel cell into one house. On the other hand, using a battery with a fuel cell increases the household energy cost, and has few effects on CO_2 emission reduction.

Keywords

Household, PV, Fuel Cell, Battery, Mixed Integer Programming

1. Introduction

The residential sector accounts for 14.3% (2051 PJ/year) of the total energy consumption in Japan [1], and 475.9 Mt CO_2 is emitted by energy consumption in the residential sector [2]. The residential sector's energy consumption has doubled since 1973, and furthermore, unit CO_2 emissions have been increasing in recent years because

*Corresponding author.

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all nuclear plants have been stopped and most electricity is generated by fossil fuel thermal power plants. Improving energy efficiency in the residential sector is a big challenge in Japan. Utilizing distributed energy resources, such as PV system, fuel cells, and batteries, encourages energy saving in the household sector. There are many prior studies on the economic and environmental impacts of introducing a PV [3]-[7], fuel cell [7]-[11], and battery [3] [6] into a household. Panayiotou *et al.* [3] examined the optimal design of a standalone PV and hybrid PV-Wind system with battery. Arboit *et al.* [4] assessed the solar energy potential at a city block in low-density urban area. Kaewniyompanit *et al.* [5] and Bozchalui *et al.* [6], on the other hand, focused on PV installation in high-density urban area, and evaluated energy costs saving and CO_2 emissions reduction of residential PV and smart grid in Japan and Canada. Shimoda *et al.* [8] and Ulleberg *et al.* [9] simulated fuel cell performance in residential sector, and examined city-level energy and CO_2 reduction effects in Japan and Norway. Hamada *et al.* [10] evaluated the performance of residential fuel cell, operated by different algorithms. Tanrioven and Alam [11] evaluated fuel cell's stable power supply for residential use. Shabani *et al.* [7] simulated the performance of combined utilization of PV and fuel cell, and carried out the system cost analysis. However, combined utilization of fuel cell, battery, and PV is not considered. In this study, we evaluate the economic and environmental effects of installing a residential PV, a fuel cell, and a battery.

2. Methods

Figure 1 shows the simulation process in this study. First, we estimate the household energy (electricity and hot water) demand by simulating the living activities of family members (2.1). We also estimate the residential PV system's electric power from observed meteorological data (2.2). Finally, we simulate the energy demand and supply of a household with various energy apparatus (fuel cell, battery, and PV) (2.3) and evaluate the effects on energy cost and CO_2 emission.

2.1. Energy Demand Estimation Based on Simulated Living Activities

Assuming that the simulated family members are an office worker, a homemaker, and two children, we simulate each member's daily activity schedules by using the Markov chain model. The concept of the model is presented in **Figure 2**. First, a member's activity at 0:00 is decided according to the member's ratio from a time use survey [12]. **Table 1** shows activity classifications and examples. Next, according to the transition probabilities of

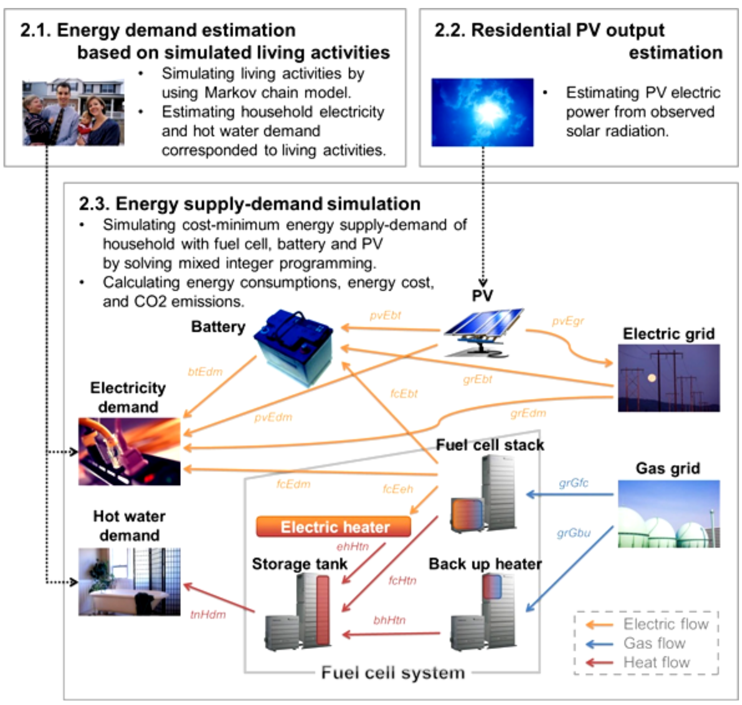


Figure 1. This study's simulation process.

Table 1. Activity classifications and their examples from the time use survey [12].

Activity classification	Some concrete examples
Sleeping	Continuous sleep for more than 30 minutes; napping
Eating	Breakfast, lunch, supper, snacks
Personal chores	Washing; going to the toilet; bathing; changing clothes; make-up; haircut
Medical treatment or recuperation	Activities related to diagnosis of illness and its treatment; hospitalization and recuperation
Working	Activities for gaining income, including preparation, clearing up, and commuting during work
Work-related association	Work-related association with senior staff, colleagues, and junior staff; welcome and farewell parties, etc.
Classes and school activities	Learning activities at school; morning assemblies; tidying up and cleaning of school; school events; school clubs; other extracurricular activities, etc.
Learning activities outside school	Learning activities at home and/or cram schools, homework
Cooking, cleaning, laundry	Preparing meals and snacks; clearing after meals; cleaning the house and yard; laundry (including ironing)
Shopping	Shopping for food; clothing; and other daily necessities
Caring for children	Childcare; education; transporting children to and from school, etc.
Miscellaneous	Sorting things out; going to banks and public offices; nursing care for family members other than children
Commuting to work	Movement between home and place of work (including fields)
Commuting to school	Movement between home and school
Social obligations	PTA, local events; meetings; ceremonial occasions; volunteer activities
Conversation/Personal association	Conversation and association with family members, friends, relatives and acquaintances in person or by telephone or e-mail
Exercise and sports	Gymnastics, physical exercise, various types of sport and ball games
Outings and walks	Visits to sight-seeing spots and shopping centers; strolling in town; other walks; angling
Hobbies, entertainment, cultural activities	Hobbies including study to gain skills or qualifications, appreciation of arts and music, watching games; play; games
Internet as hobbies, entertainment, cultural activities	Using the Internet as hobby, for entertainment or play (other than e-mail)
TV	Including the viewing of BS, CS, CATV, 1-seg
Radio	
Newspapers	Reading morning and/or evening editions of newspapers, trade journals, public relations magazines and leaflets
Magazines, comic books, books	Reading of weekly or monthly magazines, comic (books), books and catalogs
CDs, tapes	Listening to music on audio media other than radio, such as CD, digital audio player, tape, or record
Videos, HDDs, DVDs	Watching videos, HDDs, DVDs (including recorded programs)
Rest	Resting, enjoying tea or between-meals snacks, doing nothing
Other activities	Activities other than those described above

activity from 0:00 to 0:03, his or her activity at 0:03 is decided. The above processing is repeatedly performed and the activity after 3 minutes is stochastically decided from the current activity. The activity transition probabilities are also estimated from the time use survey [12]. **Figure 3** shows an example of the simulation results of the daily activity schedules of a family.

Then, we estimate 3-minute demand profiles of electricity and hot water corresponding to the simulated living activities. **Table 2** and **Table 3** show the unit consumptions of electricity and hot water. For instance, when some family members watch TV from 8:00 to 10:00, 107 W electric power consumed by the TV occurs from 8:00 to 10:00. We assume that the whole demand for space heating and cooling is provided by electrical air conditioners, and the electric consumption for space heating and cooling is calculated separately by a household

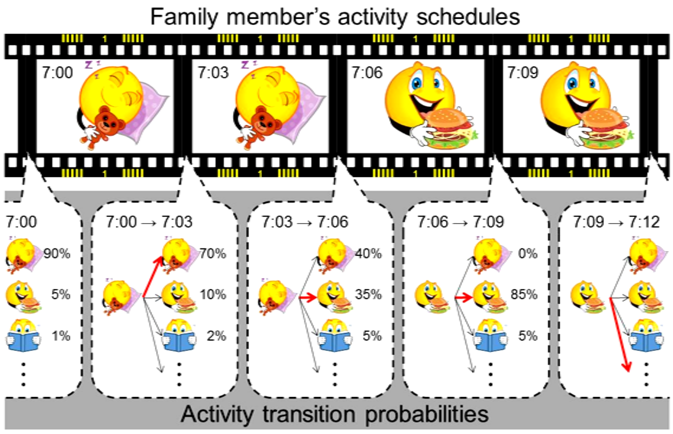


Figure 2. Daily activity schedule simulation by Markov chain model (schematic).

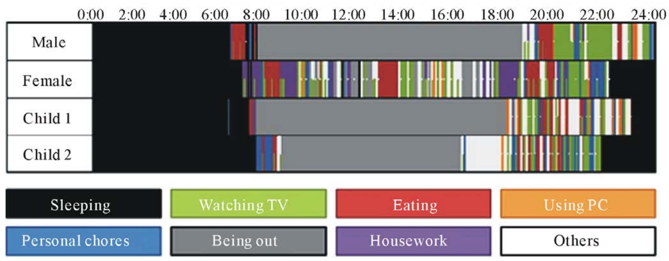


Figure 3. Example of simulated family activity schedules.

Table 2. Electric power consumption of home electric appliances.

Home electric appliance	Electric power consumption (W)
Hair dryer	775
Reading lamp	34
Microwave oven	1141
Rice cooker	1200
Laundry machine	400
Vacuum cleaner	776
Electric iron	1068
PC	50
TV	107
Radio	11
Component stereo	40
HD/DVD recorder	30
Refrigerator	80
Toilet seat	35
Others	200

heating and cooling simulation model[1]. The house where the family lives is assumed to be a detached house in Tokyo. **Figure 4** shows the estimated electric power and hot water profiles of a typical household and the average of 200 households on a summer weekday. The demand estimation every 3 minutes successfully reproduces

[1]We used SMASH software, which is developed by the Institute for Building Environment and Energy Conservation (IBEC).

Table 3. Hot water consumption by daily activities.

Activity	Hot water consumption (L/minute)			Consumption probability
	Winter	Mid-season	Summer	
Washing face	1.00	0.00	0.00	1
Bathing	1.67	2.00	2.50	1/3
Cooking	0.80	0.00	0.00	1/2
Filling the bath	6.67	6.67	6.67	1
Reheating the bath	2.67	2.67	2.67	1

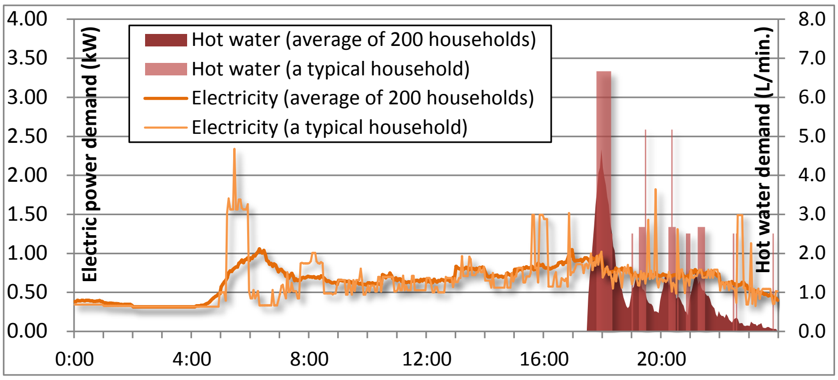


Figure 4. Electric power and hot water demand profiles on a summer weekday.

spikes from using high-energy appliances, such as a hair dryer and microwave oven.

2.2. Residential PV Output Estimation

The generated power from PV, $pvE(d,t)$, can be estimated by:

$$pvE(d,t) = \frac{R_g(d,t) \cdot T_{I_\theta} \cdot C \cdot O}{S} \tag{1}$$

where $R_g(d,t)$: Global solar radiation (kW);

T_{I_θ}: Transformation coefficient of global solar radiation into solar irradiance on a roof in each season (summer: 1.022, winter: 1.389, mid-season: 1.146);

C: Capacity of PV (kW);

O: Power factor of PV (0.7);

S: Solar radiation intensity (1.0 kW/m^3).

We use 1-minute global solar radiation data observed at the Tokyo District Meteorological Observatory [13] and estimate the 3-minute electric power from the 3.0 kW PV system in summer, winter, and mid-season. **Figure 5** shows the estimated PV electric output profile on July 27th and the average profile in summer. As shown, the PV output profile draws a smooth curve on average, whereas the electric power fluctuates greatly.

2.3. Energy Supply-Demand Simulation

We simulate energy supply-demand profiles every 3 minutes by using mixed integer programming. The target function of this programming minimizes the household energy cost. The household energy cost is composed of the initial cost of the energy apparatus ($COSTini$), electricity charge ($COSTelec.$), gas charge ($COSTgas$), and benefit from selling PV electricity ($BENEsell$):

$$COST = COSTini + COSTelec. + COSTgas - BENEsell \tag{2}$$

Monthly amortized initial costs to purchase the energy apparatus can be derived by:

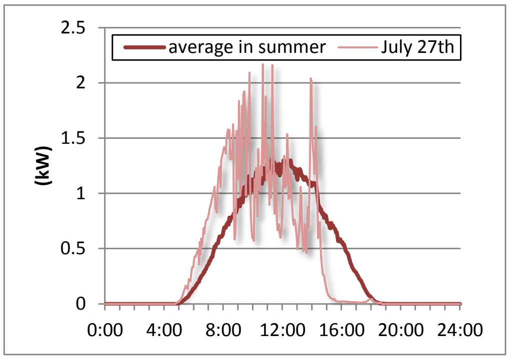


Figure 5. PV electric output profiles.

$$COSTini = \frac{1}{12}\frac{(PRICE - SUB)\times r}{1-(1+r)^{-TIME}} \tag{3}$$

where $PRICE$: Price of energy apparatus(JPY);
SUB : Subsidy of energy apparatus (JPY);
$TIME$: Lifespan of energy apparatus (year);
r : Discount rate (0.01).

The price, subsidy, and lifespan of each energy apparatus are shown in **Table 4**.

Both electricity and gas charges are the sum of the basic charge and the commodity charge, as shown in the following equations:

$$COSTelec. = CHA_{bE} + CHA_{cE}\sum_{d,t} grE(d,t) \tag{4}$$

$$COSTgas = CHA_{bG} + CHA_{cG}\sum_{d,t} grG(d,t) \tag{5}$$

where $grE(d,t)$: Grid electricity consumption at time t on day d (kWh);
$grG(d,t)$: Gas consumption at time t on day d (m^3);
CHA_{bE} : Monthly basic charge of electricity (JPY/month);
CHA_{cE} : Commodity charge rate of electricity (JPY/kWh);
CHA_{bG} : Monthly basic charge of gas (JPY/month);
CHA_{cG} : Commodity charge rate of gas (JPY/m^3).

Basic charges and commodity charge rates of electricity and gas follow TEPCO and Tokyo Gas's pricing.

The selling benefit depends on the electricity from PV back to the grid. It is obtained by:

$$BENEsell = V_{sell}\sum_{d,t} pvEgr(d,t) \tag{6}$$

where V_{sell} : Selling unit price of electricity from PV (42 JPY/kWh);
$pvEgr(d,t)$: Electricity from PV back to the grid at time t on day d (kWh).

CO_2 emissions by energy consumption are also calculated by setting the CO_2 emission basic units as below:

$$CO_2 = F_E\sum_{d,t}\left(grE(d,t) - pvEgr(d,t)\right) + F_G\sum_{d,t} grG(d,t) \tag{7}$$

where F_E : CO_2 emission basic unit of electricity (0.69 kg-CO_2/kWh);
F_G : CO_2 emission basic unit of electricity (2.21 kg-CO_2/m^3).

This mixed integer programming consists of 461,432 equations and 389,462 variables about cost, CO_2 emissions, energy balance, and household energy apparatus (fuel cell, PV, and battery). **Table 5** shows performances of our assumed household energy apparatus.

3. Results and Discussion

We simulate household energy supply and demand every 3 minutes with various combinations of energy appa-

Table 4. Price, subsidy, and lifespan of household energy apparatus.

	Price (10^3 JPY)	Subsidy (10^3 JPY)	Lifespan (year)
Gas tankless water heater	360.0	0.0	10
Fuel cell	2761.5	850.0	10
Battery	1680.0	0.0	10
PV	1740.0	144.0	20

Table 5. Household energy apparatus performances.

Apparatus	Performance	Value
Fuel cell stack	Maximum gas consumption (kW)	2.08
	Power generation efficiency	0.36
	Heat recovery efficiency	0.45
	Minimum load factor	0.33
	Maximum load factor	1.00
Back up heater	Heat recovery efficiency	0.80
Electric heater	Heat recovery efficiency	0.90
Storage tank	Capacity (L)	200
	Hot water temperature (degree C)	60
Battery	Capacity (kWh)	6.60
	Charge discharge efficiency	0.90
	Self-discharge rate (in 3 minutes)	2.00×10^{-5}
	Minimum charged rate	0.10
	Maximum charged rate	0.90
	Maximum charge discharge power (kVA)	1.50

ratus: fuel cell, battery, PV, and a conventional gas tankless water heater (efficiency = 0.80). **Table 6** shows the combinations of household energy apparatus assumed in each case in this study. In the hybrid generation (HB) and hybrid with battery (HB + BT) cases, both a fuel cell and a PV system are installed. Then, we evaluate electricity consumptions, energy costs and CO_2 emissions for six cases. We don't evaluate gas consumptions directly, but we indirectly consider the consumptions by energy costs and CO_2 emissions calculation in Equations (5) and (7).

3.1. Electric Self-Sufficiency Evaluation

Figure 6 shows the annual electricity consumptions in each case. Here, the electricity self-sufficiency rate R_{self} is calculated by:

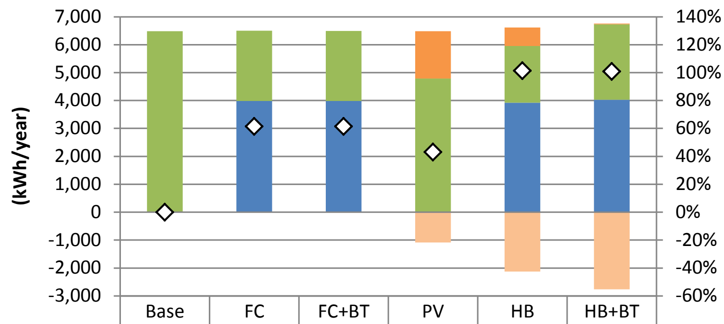
$$R_{self} = \frac{fcE + pvE}{Edm} \tag{8}$$

where fcE : Annual electricity generated from the fuel cell (kWh/year);
pvE : Annual electricity generated from the PV (kWh/year);
Edm : Annual electricity demand (kWh/year).

In the base case, the total electricity consumption of 6487 kWh is supplied from the grid. When a fuel cell is installed into the household, about 4000 kWh of electricity is generated from the fuel cell, and it provides for about 60% of the total electricity consumption in each household. When the residential PV system is introduced, surplus electricity from the PV goes back to the grid. More electricity can be reversely transmitted when the

Table 6. Combinations of household energy apparatus we assumed.

	Gas tankless water heater	Fuel cell	Battery	PV
Base case (BASE)	X			
Fuel cell (FC)		X		
Fuel cell with battery (FC + BT)		X	X	
PV	X			X
Hybrid generation (HB)		X		X
Hybrid with battery (HB + BT)		X	X	X



	Base	FC	FC+BT	PV	HB	HB+BT
back to the grid	0	0	0	-1,090	-2,124	-2,762
from PV	0	0	0	1,697	663	24
from the grid	6,487	2,513	2,509	4,790	2,036	2,705
from fuel cell	0	3,985	3,986	0	3,919	4,030
self-sufficient rate	0%	61%	61%	43%	101%	101%

Figure 6. Annual electricity supplied from household energy apparatus and from/back to the grid.

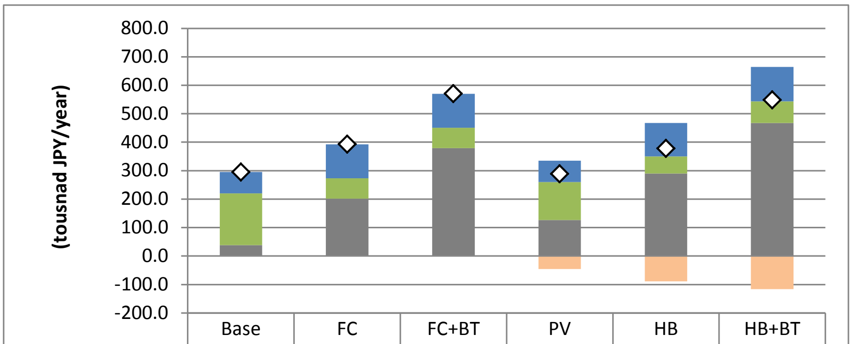
household has the hybrid generation system and battery. In the case of HB and HB + BT, electricity back to the grid is more than the purchased electricity, and thus the electricity self-sufficiency rates are over 100%. This result indicates that a household with a fuel cell and a PV system is a net-zero energy house (NZEH).

3.2. Economic Assessment

Figure 7 shows the annual energy costs in each case. First, we assess the economic effect of the fuel cell by comparing the energy cost in the FC case to that in the base case. The total energy cost is 294.9 thousand JPY/year in the base case and 392.7 thousand JPY/year in the FC case, and the annual cost increases by 97.8 thousand JPY/year when a fuel cell is installed. The cost increase is caused by the additional amortized initial cost for the fuel cell (+163.8 thousand JPY/year) and exceeds the energy charge saving (−66.0 thousand JPY/year). Next, we appraise the economic effect of using a battery with a fuel cell by comparing energy costs in the FC case and the FC + BT case. The annual energy cost is 392.7 thousand JPY/year in the FC case and 570.1 thousand JPY/year in the FC + BT case, which is about 1.5 times greater. The initial cost difference of 177.4 thousand JPY/year directly influences the total energy cost. The energy charges saved are very low because peak-load pricing is not considered. Finally, we assess the influence on the energy cost by installing a residential PV system. As a result of the comparison between the base and the PV case, or between the FC case and the HB case, we find that the energy cost slightly decreases by introducing the PV system into the household. This is mainly due to the benefit of selling surplus electricity from the PV. Although the energy charge in the HB+BT case is relatively high, this is offset by the selling benefit.

3.3. Environmental Evaluation

Figure 8 shows annual CO_2 emissions by household energy use in each case. First, we evaluate the environ-



	Base	FC	FC+BT	PV	HB	HB+BT
selling benefit	0.0	0.0	0.0	-45.8	-89.2	-116.0
gas charge	75.0	119.5	119.6	75.0	117.9	120.7
elec. charge	181.9	71.4	71.3	133.3	59.3	76.1
initial cost	38.0	201.8	379.2	126.5	290.3	467.6
total cost	294.9	392.7	570.1	288.9	378.3	548.4

Figure 7. Annual energy costs.

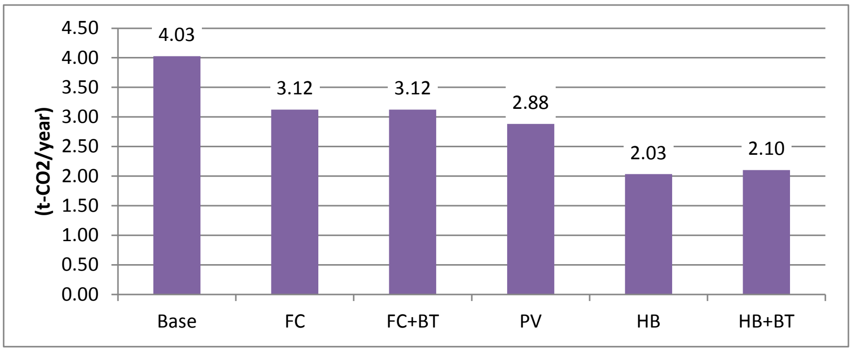


Figure 8. Annual CO_2 emissions.

mental effect of the fuel cell by comparing CO_2 emission in the FC case to that in the base case. In the base case, 4.03 t CO_2 is emitted every year; on the other hand, 3.12 t CO_2 is emitted in the FC case. Introducing a fuel cell reduces CO_2 emission by 22.4%, and its marginal cost is 108.5 thousand JPY/t CO_2. Second, we assess the environmental impact of installing the PV system. The annual CO_2 emission is 2.88 t CO_2 and a reduction of 1.95 t CO_2 emission is enabled by the residential PV system. This reduction is equivalent to 28.4% of the CO_2 emission in the base case. The marginal cost for CO_2 reduction is 34.8 thousand JPY/t CO_2, when the selling benefit is not considered. Third, we evaluate the reduction of CO_2 emission by installing the hybrid generation system. The comparison between the base case and the HB case suggests that 2.00 t CO_2, or 49.5% of CO_2 emission, can be reduced each year by the household fuel cell and the PV system. The social marginal cost excluding the selling benefit is 100.0 thousand JPY/t CO_2.

4. Conclusion

Table 7 summarizes the electric self-sufficiency, economic, and environmental effects by installing various household energy apparatus. Introducing a fuel cell and a PV enables the reduction of CO_2 emission from the residential sector, although the initial costs for purchasing these apparatus are required. The introduction cost of the residential PV system can be offset by selling surplus electricity from the PV back to the grid. On the other hand, a fuel cell costs an additional 100 thousand JPY in each year. Using a battery with a fuel cell does not have any effects on a household's electric self-sufficiency or CO_2 emission, and increases the annual energy cost by 170 - 180 thousand JPY. For further study on introducing a battery into a household, cost-driven measures such as peak load pricing have to be considered. Furthermore, we focus on economic and environmental impacts of household energy use, and we don't examine the impacts of manufacturing and disposing energy apparatus.

Table 7. Combinations of household energy apparatus we assumed.

	Fuel cell	Battery	PV	Self-sufficient rate	Energy cost (10^3 JPY/year)	CO_2 emission (t CO_2/year)
Base				0%	294.9	4.03
FC	X			61%	392.7	3.12
FC + BT	X	X		61%	570.1	3.12
PV			X	43%	288.9	2.88
HB	X		X	101%	378.3	2.03
HB + BT	X	X	X	101%	548.4	2.10

For comprehensive economic and environmental evaluation, we need to carry out macro-economic analysis and life cycle assessment (LCA) of those energy apparatuses.

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