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

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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 CO2 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 CO2 is emitted by energy consumption in the residential sector [2]. The residential sector’s energy consumption has doubled since 1973, and furthermore, unit CO2 emissions have been increasing in recent years because

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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 CO2 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 CO2 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 CO2 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.](image-url)
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 recovery |
| 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; cleaning 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.
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).
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, $p\nu E(d,t)$, can be estimated by:

$$p\nu E(d,t) = \frac{R_g(d,t) \cdot T_{g\nu} \cdot C \cdot O}{S}$$

where $R_g(d,t)$: Global solar radiation (kW);
$T_{g\nu}$: 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/m²).

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 ($COST_{ini}$), electricity charge ($COST_{elec}$), gas charge ($COST_{gas}$), and benefit from selling PV electricity ($BENEsell$):

$$COST = COST_{ini} + COST_{elec} + COST_{gas} - BENEsell$$

Monthly amortized initial costs to purchase the energy apparatus can be derived by:
where \( \text{PRICE} \): Price of energy apparatus (JPY); 
\( \text{SUB} \): Subsidy of energy apparatus (JPY); 
\( \text{TIME} \): 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:

\[
\text{COSTelec}_i = \text{CH}_E + \sum_{d,t} g_E(d,t) \\
\text{COSTgas}_i = \text{CH}_G + \sum_{d,t} g_G(d,t)
\]

where \( g_E(d,t) \): Grid electricity consumption at time \( t \) on day \( d \) (kWh); 
\( g_G(d,t) \): Gas consumption at time \( t \) on day \( d \) (m³);

\( \text{CH}_E \): Monthly basic charge of electricity (JPY/month);

\( \text{CH}_G \): Monthly basic charge of gas (JPY/month);

\( g_E(d,t) \): Commodity charge rate of electricity (JPY/kWh);

\( g_G(d,t) \): Commodity charge rate of gas (JPY/m³).

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:

\[
\text{BENE}_{\text{sell}} = V_{\text{sell}} \sum_{d,t} pvEgr(d,t)
\]

where \( V_{\text{sell}} \): 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).

\( \text{CO}_2 \) emissions by energy consumption are also calculated by setting the \( \text{CO}_2 \) emission basic units as below:

\[
\text{CO}_2 = \sum_{d,t} (g_E(d,t) - pvEgr(d,t)) + \sum_{d,t} g_G(d,t)
\]

where \( F_E \): \( \text{CO}_2 \) emission basic unit of electricity (0.69 kg-CO₂/kWh);

\( F_G \): \( \text{CO}_2 \) emission basic unit of electricity (2.21 kg-CO₂/m³).

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.

| 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 CO2 emissions for six cases. We don’t evaluate gas consumptions directly, but we indirectly consider the consumptions by energy costs and CO2 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:

\[
R_{self} = \frac{fcE + pvE}{Edm}
\]

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  |
| Hybrid generation (HB) |                         |           |         | X  |
| Hybrid with battery (HB + BT) | X                     | X         |         | X  |

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

A 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 CO₂ emissions by household energy use in each case. First, we evaluate the environ-
mental effect of the fuel cell by comparing CO2 emission in the FC case to that in the base case. In the base case, 4.03 t CO2 is emitted every year; on the other hand, 3.12 t CO2 is emitted in the FC case. Introducing a fuel cell reduces CO2 emission by 22.4%, and its marginal cost is 108.5 thousand JPY/t CO2. Second, we assess the environmental impact of installing the PV system. The annual CO2 emission is 2.88 t CO2 and a reduction of 1.95 t CO2 emission is enabled by the residential PV system. This reduction is equivalent to 28.4% of the CO2 emission in the base case. The marginal cost for CO2 reduction is 34.8 thousand JPY/t CO2, when the selling benefit is not considered. Third, we evaluate the reduction of CO2 emission by installing the hybrid generation system. The comparison between the base case and the HB case suggests that 2.00 t CO2, or 49.5% of CO2 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 CO2.

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 CO2 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 CO2 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) | CO₂ emission (t CO₂/year) |
|---------------|-----------|---------|-----|----------------------|----------------------------|--------------------------|
| Base          |           |         |     | 0%                   | 294.9                      | 4.03                     |
| FC            |           | X       |     | 61%                  | 392.7                      | 3.12                     |
| FC + BT       | X         |         |     | 61%                  | 570.1                      | 3.12                     |
| PV            |           |         | X   | 43%                  | 288.9                      | 2.88                     |
| HB            |           |         | X   | 101%                 | 378.3                      | 2.03                     |
| HB + BT       | 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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