Evaluation Research on the Introduction Effect for Various Energy Supply Systems for Detached Houses

Qingrong Liu*1 and Yuji Ryu2

1 Ph.D. Candidate, Faculty of Environmental Engineering, The University of Kitakyushu, Japan
2 Professor, Faculty of Environmental Engineering, The University of Kitakyushu, Japan

Abstract

In this paper, seven cases with three different options for energy provision, PV, co-generation and all-electrified system, have been assumed for a detached house. In order to obtain an energy-saving effect, a new theory concerning the determination of running schedule for the co-generation system has been presented. On this basis, the outcomes for various options have been evaluated regarding the energy-saving, environmental and economic effects. The results can be summarized as follows:

(1) A function relationship between the heat-to-power ratio and energy saving has been proposed. Moreover, expressions to calculate the minimum thermal utilization efficiency and the electric generating efficiency for the track electricity and track thermal operation modes also have been derived.

(2) Energy supply systems using PV can achieve excellent effects considering each evaluating index. However, because of the high initial cost, the payback period is longer than for other systems, at more than 9 years.

(3) The co-generation system can achieve energy-saving and environmental effects. In addition, with the remarkably low running cost, its payback period is less than 4 years.

(4) The energy saving and environmental effect of the all-electrified energy supply system depends on the COP/efficiency performance of electricity consumption equipment. However, the economic effect is excellent compared with the reference system.

Keywords: domestic co-generation system; heat-to-power ratio; detached house; energy supply system

1. Introduction

The depletion of fossil energy resources and pollution of the environment have created an interest in developing high efficiency energy systems such as co-generation systems and PV systems, as well as new equipment for residences.

Small domestic co-generation equipment has been put into commercial service in Japan. PV systems also have been introduced in detached houses. Furthermore, new technological equipment, such as domestic CO2 heat pump hot water heaters and high efficiency equipment have also started to be used. Through the use of these new techniques and equipment, some kinds of high efficiency energy supply systems can be introduced in detached houses. Currently, there are some studies regarding domestic fuel cell co-generation systems. KUROKI analyzed the introduction effect of co-generation systems for various regions in Japan [1]. TANAKA researched the planning and design of co-generation systems for residences [2-5]. MAEDA discussed the environmental load reduction of PV and gas co-generation systems [6]. However, the design policy for optimal running schedules for domestic co-generation systems has not been decided. Furthermore, very little research has been done on the optimization combination of new systems and high efficiency equipment.

In this research, the introduction effects of three different kinds of energy supply systems with various types of new high efficiency equipment for a detached house have been compared. Seven cases with different energy systems or efficiency have been introduced in detached houses. Currently, there are some studies regarding domestic fuel cell co-generation systems. KUROKI analyzed the introduction effect of co-generation systems for various regions in Japan [1]. TANAKA researched the planning and design of co-generation systems for residences [2-5]. MAEDA discussed the environmental load reduction of PV and gas co-generation systems [6]. However, the design policy for optimal running schedules for domestic co-generation systems has not been decided. Furthermore, very little research has been done on the optimization combination of new systems and high efficiency equipment.

In this research, the introduction effects of three different kinds of energy supply systems with various types of new high efficiency equipment for a detached house have been compared. Seven cases with different energy systems or efficiency have been evaluated regarding energy saving, environmental and economic effects. Furthermore, a novel theory regarding the influence of the heat-to-power ratio on the energy saving for the co-generation system has been presented. The theory can be used to determine the running schedule of the domestic co-generation system.

2. Object of Simulation and Load Assessment

The simulation object is a detached house, which was assumed to be a standard house model proposed by AIJ (Architectural Institute of Japan). The external structure was assumed to satisfy the reference value for...
the summer irradiation acquisition coefficient and the heat loss coefficient at Yahatanishi-ku in Kitakyushu provided in the standard for the next-generation energy saving.

The hourly electricity and heat load were calculated by using two pieces of software. One was the air-conditioning load calculating software THERB, developed by OZAKI [7]. The other was the life schedule operation generator SCHEDULE Ver2.0, proposed by SHASE (the Society of Heating Air-conditioning and Sanitary Engineers of Japan). The hot water load was calculated by using the seasonal hot water amount, hot water temperature and the utility water temperature. The hot water amount and temperature data were assumed according to SCHEDULE Ver2.0.

### 3. Case Setting

#### 3.1 Description of various cases

Table 1. contains the energy system details of various simulation cases. Table 2. is the assumed COP/efficiency performance of equipment to be used in the energy systems. As Table 1. shows, kitchen equipment consists of a gas stove in case 1 to case 4, while an IH cooking heater is used for cooking in case 5 to case 7.

CASE 1 is assumed to be a conventional system. As Table 1. shows, the electricity load consists of the electricity consumption of the cooling load, lighting and home appliances. The heat load includes the heating load and the hot water load. The electricity demand is satisfied by the utility electricity and a gas hot water boiler supplies the heat load.

CASE 2 AND CASE 3 are a co-generation system. Electricity and heat loads for the two cases are the same as those for case 1. However, the heat load is supplied by the recovered heat from the co-generation system. The utilization efficiency of the recovered heat is assumed as 0.7. The co-generation operation mode is assumed as track electricity. The shortfall in electricity is purchased from the grid of utility electricity. An auxiliary gas hot water heater will satisfy the shortage of thermal load. The running schedule of the co-generation system will be discussed in section 3.2.

CASE 4 AND CASE 5 are the cases in which a PV system is introduced. The capacity of the PV systems for both cases is 3.2kW. The heating and cooling loads are supplied by an air-conditioner using electricity in both cases. The energy of case 4 is provided by the PV system and natural gas. As Table 1. shows, it uses the gas hot water heater to supply hot water for the bath and cooking. However, the total energy demand in case 5 is provided by electricity. Furthermore, a CO2 heat pump hot water heater is introduced in the energy system in case 5.

In CASE 6 AND CASE 7, the electricity is purchased from the grid of utility electricity to provide all the energy demand. In this paper, such an energy supply system is called an all-electrified system. However, in case 6, a CO2 heat pump hot water heater has been introduced and hot water is supplied by an electric hot water heater in case 7.

#### 3.2 The influence of the heat-to-power ratio on energy saving in a co-generation system
3.2.1 Theory research

In order to obtain energy saving, the running schedule is very important when introducing a co-generation system. However, the method for determining a reasonable running schedule has been little researched. In this paper, a method has been proposed by using the ratio of heat to power to determine the running schedule. The ratio of heat to power achieving energy saving effect depends on the efficiency characteristics of all equipment and the operation mode (track electricity and track thermal) of the co-generation system.

As Fig. 1 shows, the co-generation system and the reference system are used to satisfy the same electricity and heat load. Energy in the left figure is consumed by the co-generation system, and that in the right is used in the reference system. Generally, the co-generation equipment cannot supply all the electricity and heat demand. Therefore, the energy saving only derives from the part of the energy consumption used for the electricity and heat demand provided by the co-generation equipment. The amount of energy saving can be described as the expression (1).

\[ \Delta F = (F_{Q,1}^0 + F_{P,1}^0) - F_{CGS} \]  

In this expression, \( (F_{Q,1}^0 + F_{P,1}^0) \) is the energy consumption in the reference system to satisfy the electricity and heat load supplied by co-generation equipment. To satisfy the whole electricity and heat load, the energy consumption of the co-generation system is described in the expression (2).

\[ E_{CGS} = F_{CGS} = F_{P,1}^0 + F_{Q,1}^0 + F_{Q,2}^0 \]  

Similarly, the energy consumption of the reference system for the total electricity and heat demand can be described in the expression (3).

\[ E_{ref} = F_{ref}^P + F_{ref}^Q + F_{ref}^P + F_{ref}^Q \]

Hence, the energy saving ratio of the co-generation system is described by the expression (4). In this paper, it is called the integrated energy saving ratio.

\[ \varepsilon_{int} = \frac{E_{ref} - E_{CGS}}{E_{ref}} = \frac{\Delta F}{F_{P,1}^0 + F_{Q,1}^0 + F_{P,2}^0 + F_{Q,2}^0} \]  

However, the energy saving ratio of co-generation equipment is defined as the expression (5), which is only the energy saving for that part of the electricity and heat load derived from co-generation equipment. It is called the co-generation energy saving ratio. If the co-generation energy saving ratio is larger than zero, the co-generation system can achieve an energy saving effect.

\[ \varepsilon_{CGS} = \frac{F_{P,1}^0 + F_{Q,2}^0 - F_{CGS}}{F_{P,1}^0 + F_{Q,2}^0} = 1 - \frac{F_{CGS}}{F_{P,1}^0 + F_{Q,2}^0} \]

Introducing the efficiencies of the co-generation and reference systems, the expressions (6) and (7) can be written as

\[ Q_{CGS} = F_{CGS} \times \eta_{CGS}^Q = F_{ref}^Q \times \eta_{ref}^Q \]
According to the expressions (6) and (7), the expressions (8) and (9) can be expressed as follows:

\[ F_{\text{ref}}^Q = \frac{F_{\text{CGS}}}{\eta_{\text{CGS}}^Q} \eta_{\text{ref}}^Q \]  

(8)

\[ F_{\text{ref}}^p = \frac{F_{\text{CGS}}}{\eta_{\text{CGS}}^p} \eta_{\text{ref}}^p \]  

(9)

According to the expressions (8) and (9), the expression for the co-generation energy saving ratio can be written as

\[ e_{\text{eg}} = 1 - \frac{1}{\eta_{\text{CGS}}^Q + \eta_{\text{CGS}}^p} = 1 - \frac{\eta_{\text{ref}}^Q \eta_{\text{ref}}^p}{\eta_{\text{CGS}}^Q \eta_{\text{ref}}^p + \eta_{\text{CGS}}^p \eta_{\text{ref}}^Q} \]  

(10)

In order to achieve energy saving, the restriction \( e_{\text{eg}} \geq 0 \) should be satisfied. As a result, the efficiencies of the co-generation equipment and reference system should satisfy the limitation of the expression (11).

\[ \frac{\eta_{\text{CGS}}^Q}{\eta_{\text{ref}}^Q} + \frac{\eta_{\text{CGS}}^p}{\eta_{\text{ref}}^p} \geq 1 \]  

(11)

The heat-to-power ratio of co-generation \( \lambda_{\text{CGS}} \) can be described by

\[ \lambda_{\text{CGS}} = \frac{Q_{\text{CGS}}}{P_{\text{CGS}}} = \frac{F_{\text{CGS}} \times \eta_{\text{CGS}}^Q}{P_{\text{CGS}} \times \eta_{\text{CGS}}^p} \]  

(12)

When the operation mode is track electricity, the power generation efficiency \( \eta_{\text{CGS}}^p \) can be considered as an already known condition. And so, the restriction of thermal recovered utilization efficiency can be described in the expression (13):

\[ \eta_{\text{CGS}}^p \geq \eta_{\text{ref}}^p (1 - \frac{\eta_{\text{CGS}}^Q}{\eta_{\text{ref}}^Q}) \]  

(13)

Introducing the ratio of heat to power \( \lambda_{\text{CGS}} \), the energy-saving restriction of the heat-to-power ratio for the track electricity operation mode can be written as

\[ \lambda_{\text{CGS}} \geq \eta_{\text{ref}}^Q \left( \frac{1}{\eta_{\text{CGS}}^Q} - \frac{1}{\eta_{\text{ref}}^Q} \right) \]  

(14)

Similarly, when the operation mode is track thermal, the restriction of electric generation efficiency is described in the expression (15). The restriction of the heat-to-power ratio is the expression (16).

\[ \eta_{\text{CGS}}^p \geq \eta_{\text{ref}}^p (1 - \frac{\eta_{\text{CGS}}^Q}{\eta_{\text{ref}}^Q}) \]  

(15)

\[ \frac{1}{\lambda_{\text{CGS}}} \geq \eta_{\text{ref}}^Q \left( \frac{1}{\eta_{\text{CGS}}^Q} - \frac{1}{\eta_{\text{ref}}^Q} \right) \]  

(16)

The symbols and descriptions in expressions (1) - (16) and Fig.1. are shown in Table 3.

### 3.2.2 Running schedule of Co-generation system

At present the domestic co-generation system cannot liberally output surplus electricity to the grid of utility electricity in Japan. This means the utility electricity supplies the shortage of electricity in the domestic co-generation system; however, it does not receive surplus electricity from the domestic co-generation system. Hence, in this paper, the operation mode of the co-generation system is assumed as track electricity, which means that co-generation equipment will be operated to satisfy the electricity load. The heat efficiency of the reference system is assumed as 80\% and the electricity generation efficiency of the utility electricity is 39.3\%. The characteristic parameters of co-generation are shown in Table 4. Based on these parameters and expression (13), the thermal recovered utilization efficiency of co-generation must be larger than 39.29\%. According to expression (14), only when the heat-to-power ratio is larger than 1.96, can the co-generation system achieves energy saving compared to the reference system.

In the co-generation system, there are two kinds of heat-to-power ratio. One is the ratio of the demand site; the other is the ratio of the co-generation equipment site. According to the performance of the co-generation equipment shown in Table 4., the heat-to-power ratio for the co-generation equipment site is 3.25 in theory. The hourly heat-to-power ratio in different periods on the demand site is calculated and shown in Fig.2. to Fig.4. In these Figures, the circle displays the percentage of days on which the hourly ratio of heat to power is above certain special values. The curves are certain ratios of heat to power for every one-hour period. It can be found that there are some hours in which the heat-to-power ratio (demand site) is larger than 3.25 (equipment site). In these hours, the recovered heat from co-generation cannot satisfy the heat demand. For Table 4. Performances of Co-generation Equipment

| Capacity | Maximum recovered thermal energy | Efficiency | Thermal recovery efficiency |
|----------|---------------------------------|------------|---------------------------|
| 1kW      | 3.25kW                          | 20%        | 65%                       |

![Fig.2. Heat-to-power Ratio in Heating Period](image-url)
this reason, a hot water tank is attached to the domestic co-generation system. The surplus heat in other hours (when the heat-to-power ratio is less than 3.25) should be stored to satisfy the heat demand shortage described above.

Considering the above condition and the yearly operation rate of co-generation equipment, two cases of co-generation system were set in this paper, which are CGS (1.0) and CGS (1.5). CGS (1.0) means the demand site ratio of heat to power is larger than 1.0 and CGS (1.5) means the demand site ratio of heat to power is larger than 1.5.

In order to determine the running schedule of these two cases, two limited restrictions to run the co-generation equipment in some one-hour periods are set. One is that the percentage of days on which the hourly heat-to-power ratio is larger than 1.0 or 1.5 must be more than 80%; at the same time, considering the partial load performance of the co-generation equipment, the electricity load of this hour must be larger than 0.25kW. For example, as Fig.2. shows, although the heat-to-power ratio restriction is satisfied at 4:00-10:00, 12:00-13:00, 15:00-16:00 and 19:00-22:00, the electricity load of the three hours at 4:00-5:00, 9:00-10:00 and 15:00-16:00 is less than 0.25kW. Therefore, the running schedule of both cases is at 5:00-9:00, 12:00-13:00 and 19:00-22:00 in the heating period. Similarly, the running schedule for other periods for co-generation systems is set as shown in Table 5.

3.3 Model of PV

The PV system is a multi-crystal silicone solar battery; its capacity is 3.2kW (panel area is 25.7 m$^2$). The installation angle is 20° and facing south. The amount of power generated by the PV system can be calculated by the following expressions [8].

$$W = \eta \times K \times I \times A \times \eta_{IN}$$

$$K = 1 - 0.0037(T_c - 25)$$

$$T_e = T_u + (-6.036 + 0.274V + 0.07IV^2)$$

$$+ I \times (45.63 - 5.91V + 0.333V^2)$$

$$E > 0.3KW \quad \eta_{IN} = 5.99 \times \ln(E) + 90.1$$

$$E < 0.3KW \quad \eta_{IN} = 20.5 \times \ln(E) + 105.2$$

But, $E = \eta \times K \times I \times A$

Where,

- $W$: Power generation amount, kWh;
- $\eta$: Module conversion efficiency, assumed as 13.3%;
- $K$: Temperature coefficient;
- $I$: Area of panel, m$^2$;
- $T_c$: Cell temperature, °C;
- $T_a$: Air temperature, °C;
- $\eta_{IN}$: Inverter efficiency, %;
- $V$: Wind velocity, m/s;

In this paper, the standard year of AMeDas meteorological data for Yahata, Kitakyushu, is used to calculate the amount of power generated by the PV system.

3.4 Units and parameters

In order to evaluate the environmental effect of various cases, the units of CO$_2$ emissions for different energy sources are shown in Table 6. Following the discussion of paper [9], the CO$_2$ units used for utility electricity were the average value for fired power plants. The prices of different energy sources are shown in Table 7. to Table 10. The equipment prices are shown in Table 11 [10]-[15].
4. Simulation Results

Indexes described in the appendix were used to evaluate the energy-saving, environmental and economic effects of these cases compared with a conventional system.

4.1 Energy saving

Fig. 5 shows the energy-saving effect of various cases compared with case 1. As the figure shows, it can be found that cases with a PV system (case 4 and case 5) have lower annual energy consumption than other cases. In case 5, in particular, energy consumption is 55.51 GJ/year and the energy saving rate reaches 30.36%. Case 2 and case 3 use cogeneration equipment and they achieve 7.82% and 6.78% energy saving rates, respectively. In the cases of the all-electrified system using utility electricity, case 6 achieves a 5.78% energy-saving rate; however, the energy saving rate for case 7 is -30.23%. The reason is that the hot water is supplied by an electric hot water heater with an efficiency of 0.95 in case 7, while in case 6, the hot water is supplied by a CO₂ heat pump hot water heater with COP 3.0.

In terms of energy utilization efficiency, cases using a PV system gain high value because it uses free solar energy. Case 5 achieves the highest energy utilization efficiency value, 89.93%, followed by case 4 with 86.89%, case 3 with 67.95%, case 2 with 67.18%, case 6 with 66.47%, case 1 with 58.12%, and case 7 with 48.09%. Although case 6 and case 7 are both all-electrified energy supply systems, the energy utilization efficiency of case 6 and case 7 is different because of the difference in the hot water supply equipment.

4.2 Environmental effects

The environmental effect of various cases is evaluated in terms of the CO₂ emission. Fig. 6 shows the amount of annual CO₂ emission and the CO₂ reduction rate compared with case 1. From Fig. 6, it can be found that the energy supply systems with a PV system are the most environmentally friendly systems, for the emission of CO₂ is lowest when compared with other energy supply systems. Case 4 achieves a 25.55% CO₂ reduction rate, and case 5 achieves 16.44%. The energy supply system with cogeneration equipment also gains good environmental effects: the CO₂ reduction rates for case 2 and case 3 are 10.55% and 12.41%. However, because the original CO₂ value for utility electricity is the average value of fired power plants, the all-electrified systems have a negative CO₂ reduction rate. In case 7, the highest amount of CO₂ (7,454 kg/year) is emitted. According to the environmental effect analysis, it can be concluded that the distributed energy system can gain better environmental effect than the energy supply system which only uses the utility energy source. However, the utility grid is an indispensable auxiliary for any kind of distributed energy system. Furthermore, high efficiency equipment such as a CO₂ heat pump hot water heater is also efficacious for the reduction of CO₂ emissions.

Table 7. Price of Natural Gas for Normal User from a Major Gas Company in Kyushu

| Volume (m³) | Initial fee (Yen/month) | Price (Yen/m³) |
|------------|-------------------------|---------------|
| 0-15       | 871.5                   | 203.58        |
| 15-30      | 1092                    | 188.85        |
| 30-100     | 1533                    | 174.15        |
| More than 100 | 1795.5           | 171.53        |

Table 8. Price of Natural Gas for Co-generation User from a Major Gas Company in Kyushu

| Initial fee (Yen/month) | Price (Yen/m³) |
|-------------------------|---------------|
| 2887.5                 | 67.62         |

Table 9. Price of Utility Electricity for Normal Users from a Major Electric Power Company in Kyushu

| Amount consumed (kWh) | Price (Yen/kWh) |
|-----------------------|----------------|
| 0-120                 | 15.54          |
| 120-300               | 19.95          |
| More than 300         | 21.40          |
| Initial fee for 40A (Yen/month) | 1134 |

Table 10. Price of Utility Electricity for All-electrified User from a Major Electric Power Company in Kyushu

| Time                     | Price (Yen/kWh) |
|--------------------------|----------------|
| 22:00-8:00               | 6.93           |
| 8:00-10:00; 17:00-22:00   | 20.48          |
| 10:00-17:00 In summer     | 32.60          |
|                         other seasons | 27.25          |
| Initial fee (Yen/month)  | 1155           |

Table 11. Price of Various Pieces of Equipment

| Equipment                        | Price (x 10⁴ Yen/unit) |
|----------------------------------|------------------------|
| Air-conditioner                  | 23                     |
| Floor heating system (living room) | 27.438                |
| Electric hot water heater        | 17.525                 |
| Gas hot water boiler (for heating & hot water) | 46.368                |
| Gas hot water heater (for hot water) | 21.596                |
| CO₂ heat pump hot water heater   | 69.840 (52,470)*       |
| IH cooking heater                | 25.935                 |
| Gas Stove                        | 1,092                  |
| Gas engine co-generation         | 82,026 (63,026)*       |
| PV system (Yen/kWh)              | 67                     |

*Note: The Price in ( ) must be paid by the user, which is the total cost minus the subsidy.
4.3 Economic effect

Fig. 7. shows the running costs and the running cost reduction rates for various cases. Similarly to the energy-saving and environment effects, the energy supply system including the PV system has the lowest running cost among these energy systems. The annual running cost of case 5 is only 36,444 yen/year with a 86.72% reduction rate. The PV and gas joint energy system (case 4) also achieves a 52.65% running cost reduction rate. Case 2 and case 3 achieve about a 38% running cost reduction rate. The running cost of the electricity system in case 6 and case 7 is less than in case 1. Case 6 gains a 44.72% running cost reduction rate, which is larger than in case 7. This can be explained by the fact that less electricity is purchased from the grid of utility electricity in case 6 because of the introduction of a high efficiency hot water heater—the CO$_2$ heat pump hot water heater.

Evaluating only the running cost is not comprehensive enough for an economic evaluation. Therefore, the initial costs for various energy supply systems are estimated roughly and are shown in Table 12. From these data, it can be concluded that the energy supply system with PV system has the highest initial cost and the lowest running cost. The initial cost of case 4 is 329.09 x 10$^4$ yen and it is 384.81 x 10$^4$ yen for case 5. However the running costs for case 4 and case 5 are 13 x 10$^4$ yen/year and 3.64 x 10$^4$ yen/year respectively. The payback periods for case 4 and case 5 are 11.22 and 9.15 years respectively. They are longer than for other energy supply systems. Although the energy supply systems with co-generation equipment in case 2 and case 3 have the same initial cost for the same equipment, because of the different running schedules, the running cost for two systems is different. The payback period for case 2 and case 3 is only 3.69 and 3.66 years. Case 6 has a little higher initial cost than case 1 and its payback period is 0.29 years. On the other hand, the initial cost and the running cost of case 7 are both lower than those of case 1.

5. Conclusion

In this paper, seven cases with three different options for energy provision, a PV, co-generation and all-electrified system, have been assumed for a detached house in the moderate and humid region of Kyushu, Japan. The evaluation research on the introduction effect of the various cases described has been carried out considering the energy saving, environmental and economic effects. Furthermore, a theory concerning the influence of the heat-to-power ratio on energy saving for the co-generation system has been presented. By using the above theoretical method, the problem of setting the running schedule for co-generation system cases has been resolved. The results can be summarized as follows:

(1) The relationship profiles between the heat-to-power ratio and energy saving change with the efficiencies and operation mode of a co-generation system. Both the minimum thermal utilization efficiency achieving energy saving for the track electricity operation mode and the minimum electricity generation efficiency achieving energy saving for the track thermal mode can be calculated by assuming the efficiency values. The energy-saving effect has been gained by using the theoretical method to determine the running schedule of the co-generation system in this research. The result proved that the theoretical method is available to determine the running schedule of domestic co-generation systems.

| Item                          | Unit | Case1  | Case2  | Case3  | Case4  | Case5  | Case6  | Case7  |
|-------------------------------|------|--------|--------|--------|--------|--------|--------|--------|
| Initial cost                  | 10$^4$ Yen | 166.90 | 205.15 | 205.15 | 329.09 | 384.81 | 170.41 | 135.46 |
| Increase in initial cost over case 1 | 10$^4$ Yen | —      | 16.66  | 16.66  | 162.19 | 217.91 | 3.51   | -31.44 |
| Running cost                  | 10$^4$ Yen/year | 27.45  | 17.10  | 17.00  | 13.00  | 3.64   | 15.18  | 21.34  |
| Reduction in running cost from case 1 | 10$^4$ Yen/year | —      | 10.35  | 10.46  | 14.45  | 23.81  | 12.28  | 6.11   |
| Payback year                  | Year | —      | 3.69   | 3.66   | 11.22  | 9.15   | 0.29   | -5.15  |
(2) The energy supply systems with PV (case 4 and case 5) can achieve an excellent introduction effect in every aspect of evaluation. Case 5 with PV and a CO\textsubscript{2} heat pump hot water heater has the best energy saving rate with 30.36% and a remarkable running cost reduction ratio with 86.72%. The best environmental effect occurred in case 4 with PV and gas equipment. However, the payback period for the high initial cost of PV is more than 9 years.

(3) The co-generation system (case 2 and case 3) also can achieve about 7% energy saving rate and above a 10% CO\textsubscript{2} reduction rate. At the same time, the running cost reduction rate is over 37%. Therefore, the payback periods of case 2 and case 3 are only 3.69 and 3.66 years respectively.

(4) The energy-saving and environmental effects of the all-electrified energy supply system are obviously dependent on the COP/efficiency performance of electric equipment. Hence, high efficiency equipment should be introduced in such an energy supply system. Nevertheless, the economic effect is excellent because of the low running cost, compared with the reference system.

References
1) Kuroki, H., Asaki, A., Niina, K., Watanabe, T., Akashi, Y. and Takaguchi, H. (2004) Study on Effects of Housing Polymer Electrolyte Fuel Cell Co-generation system. AJJ Kyushu Chapter Architectural Research Meeting (Environment), 44, (2), pp.221-224.
2) Tanaka, H. et al. (2003) Study on Planning and Design of Co-generation System for Residence Part 1 Examination on Operation Method of Generator and How to Use of Surplus Generated Power. Summaries of Technical Papers of Annual Meeting Architectural Institute of Japan, D-2, pp.327-328.
3) Adachi, T. et al. (2003) Study on Planning and Design of Co-generation System for Residences Part 2 Examination on the System Efficiency Depending on Various Residential Heat and Electric loads. Summaries of Technical Papers of Annual Meeting Architectural Institute of Japan, D-2, pp.329-330.
4) Ishibashi, R. et al. (2003) Study on Planning and Design of Co-generation System of Residence Part 3 A Design Method of Co-generation System for Residence. Summaries of Technical Papers of Annual Meeting Architectural Institute of Japan, D-2, pp.331-332.
5) Adachi, T. et al. (2004) Study on Planning and Design of Co-generation System for Residence Part 4 Study on Planning Method Considering Relationship Between Component Capacity and Operation. Summaries of Technical Papers of Annual Meeting Architectural Institute of Japan, D-2, pp.1363-1364.
6) Maeda, T., Hayashi, T., Kojima, S. and Nomura, K. (2005) Environmental Load Reduction of Photovoltaic and Gas-cogeneration. AJJ Kyushu Chapter Architectural Research Meeting (Environment), 44, (2), pp.225-228.
7) Ozaki A. Watanabe, T., Iwaoka, S. and Takase, S. (2001), Simulation Software to Describe the Thermal Environment of Residential Buildings Based on Detailed Physical Models, The Canadian Conference on Building Energy Simulation, pp.66-73.
8) Ryu, Y. and Liu, Q. (2004) A Project of Symbiotic Housing and a Simulation on Effects of Residential PV System in Kitakyushu Science and Research Park. Proceeding of JSES/JWEA Joint Conference, pp.227-230.
9) Tsurusaki, T. and Nakagami, H. (2000), Examination on Emission Original Unit of CO\textsubscript{2} Used for the Evaluation on Countermeasures for Global Warming. JSER Thesis Collection of the 19th Research Symposium Lecture, pp.159-162.
10) Foundation Economic Research Association. (2002), Estimate at the Design of the Dwelling and Shop Pocket version, pp.784-833.
11) http://www.casanavi.co.jp/customer/eco
12) http://www.hptcj.or.jp/ecocute/introduction/top.html
13) http://www.saibugas.co.jp/ecowill/kakaku.html
14) http://www.gas.or.jp/gasengine/teigakuyo.pdf
15) http://www.solar.nef.or.jp/josei/m15_price.html

Appendix: Description of evaluation indexes

\textbf{Energy saving ratio:}
\begin{equation}
E_{\text{save},i} = \frac{E_{\text{case}1} - E_{\text{case}i}}{E_{\text{case}1}} \quad (i = 2 \text{ to } 7)
\end{equation}

\textbf{Energy utilization efficiency:}
\begin{equation}
\eta_{\text{gen},i} = \frac{P_{\text{use},i} + Q_{\text{use},i}}{E_{\text{gen},i}} \quad (i = 1 \text{ to } 7)
\end{equation}

\textbf{CO\textsubscript{2} reduction ratio:}
\begin{equation}
CO2_{\text{reduce},i} = \frac{CO2_{\text{case}1} - CO2_{\text{case}i}}{CO2_{\text{case}1}} \quad (i = 2 \text{ to } 7)
\end{equation}

\textbf{Running cost reduction ratio:}
\begin{equation}
RC_{\text{reduce},i} = \frac{RC_{\text{case}1} - RC_{\text{case}i}}{RC_{\text{case}1}} \quad (i = 2 \text{ to } 7)
\end{equation}

\textbf{Payback year:}
\begin{equation}
Y_{\text{pay},i} = \frac{IC_{\text{case}1} - IC_{\text{case}i}}{RC_{\text{case}1} - RC_{\text{case}i}} \quad (i = 2 \text{ to } 7)
\end{equation}

Where,
- $E_{\text{case}1}$: Primary energy consumption of case 1;
- $E_{\text{case}i}$: Primary energy consumption of case $i$;
- $P_{\text{use}}$ and $Q_{\text{use}}$: Electricity load and Heat load;
- $CO2_{\text{case}1}$: CO\textsubscript{2} emission amount of case 1;
- $CO2_{\text{case}i}$: CO\textsubscript{2} emission amount of case $i$;
- $RC_{\text{case}1}$: Running cost of case 1;
- $RC_{\text{case}i}$: Running cost of case $i$;
- $IC_{\text{case}1}$: Initial cost of case 1;
- $IC_{\text{case}i}$: Initial cost of case $i$;