Long-Term Prediction System of Urban CO_2 Emission for Supporting the Reduction Policies Part 2. CO_2 Reduction Through PV Support Policies

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ABSTRACT

A long-term prediction system of urban CO_2 emissions has been built by our project team to support the implementation of CO_2 emission reduction policies. The model is constructed using a system dynamics method that is a computer-aided approach to policy analysis and design. In part 1, other project members presented the method for model construction and the results of its application to a small-scale city. The objective of this study is to determine the effect of different photovoltaic (PV) policies on reducing CO_2 emissions in the residential sector, which has a 40 % emission reduction target. PV has shown high growth in the energy supply sector and a large CO_2 reduction effect, particularly in conjunction with supporting policies used to promote energy-saving technologies, such as feed-in tariffs (FIT) and subsidies. To determine the effects of these different supporting policies, a PV selection rate equation was added to the model using various assumptions. We examined three scenarios that combine a variety of policies. The simulation results show that CO_2 emissions can be reduced by between 4 % and 12 % when applying these scenarios. Through the use of our long-term prediction model, we can clearly illustrate the degree of PV-related CO_2 emission reduction for each policy combination.

KEYWORDS

Long-term prediction system, System dynamics, Urban CO_2 emissions, Scenario studies, Policy support

Nomenclature

AP: Annual amount of power generation [kW/year]
B: Electricity bill [JPY/kWh]
C: CO_2 emissions of the residential sector [t-CO_2]

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C_{BA}: Basic CO_2 emissions per apartment household [t-CO_2/household· year]
C_{BD}: Basic CO_2 emissions per detached house household [t-CO_2/household· year]
C_{PV}: CO_2 emissions per detached house with PV [t-CO_2/household· year]
ES: Electricity sales rate [-]
FIT: Procurement cost [JPY/kWh]
HA: Number of apartments
HD: Number of detached houses
i: Elapsed time from 1990
i-1: The year previous to *i*
N: The number of detached houses available for new purchase
PP_B: PV payback period by basic condition [year]
PP_S: PV payback period by scenario condition [year]
PR: PV integration rate [-]
PV: PV price [JPY/kWh]
S: Subsidy price [JPY/household]
SC: Self-consumption rate [-]
SR: PV selection rate [-]
TPR: Thermal power rate in power supply [-]
x: Elapsed time from 1990 (*i*-1990)

INTRODUCTION

Japan has a goal to reduce greenhouse gas emissions by 26 % from fiscal year (FY) 2013 to FY 2030. In particular, the residential sector has set a carbon dioxide (CO_2) reduction target of approximately 40 %. To meet this goal, it is important to determine how to reduce CO_2 using a variety of technologies, as a result of the policy budget being limited. Thus, the objective of this study is to determine the effect of different photovoltaic (PV) policies on reducing CO_2 emissions in the residential sector.

TARGET CITY FOR CASE STUDY

The target city of this study is Kashiwa, Japan, the location of which is shown in Figure 1, and general information is shown in Table 1. Kashiwa is a major city of approximately 420,000 people, located in the north of Chiba prefecture. Kashiwa serves as a commuter town for Tokyo because it is located less than an hour away by train to the northeast. Furthermore, population is increasing because of development of urban infrastructure, and the convenience of accessibility from other provinces. Policies for reducing CO_2 emissions in the residential sector are urgently required as

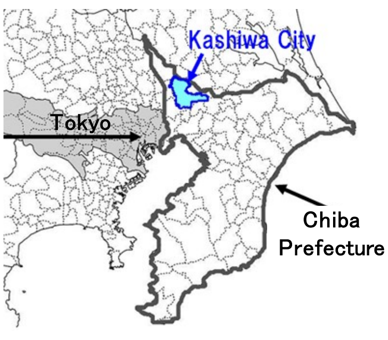

Figure 1. *Location of Kashiwa*

Table 1. *Basic information of Kashiwa*

Area (㎢)	115
Population (person)	420,000
Population density (person/㎢)	3,630
Households (the number of households)	148,043

the number of households and the energy consumption per household are both increasing.

ACCURACY VERIFICATION OF LONG-TERM PREDICTION MODEL

Due to space limitations, we explain the part of the model in Figure 2. An object variable was calculated by the multiplication of the graph functions that it was defined as the relationship between the object variable and explanatory variable. In order to confirm the accuracy of the model, simulation values were compared to actual values from 1990 to 2010. Results regarding the number of houses and the number of households are classified by housing type, as shown in Figures 3 and 4. The average error rate was 20 % or less, and all modeled values captured the trend of the actual values well. Therefore, we conclude that the model can effectively predict long-term trends. Figures 3 and 4 indicate that the number of households and houses are increasing.

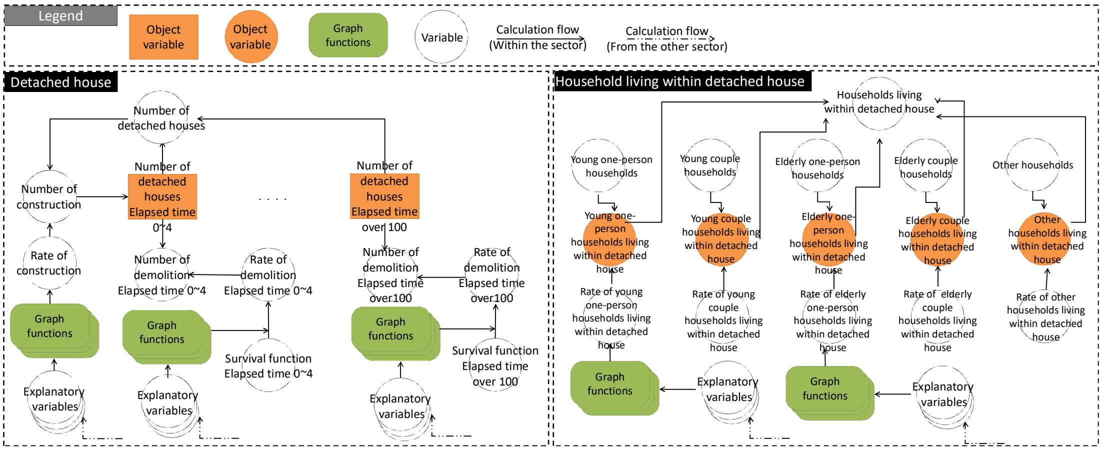

***Figure 2**. The prediction model of number of detached house and household living within detached house*

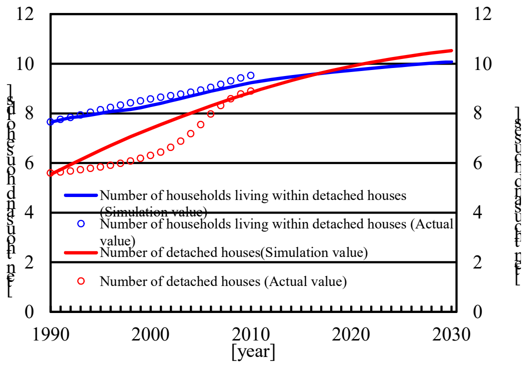

***Figure 3.** The number of the detached houses and households that live in the detached house*

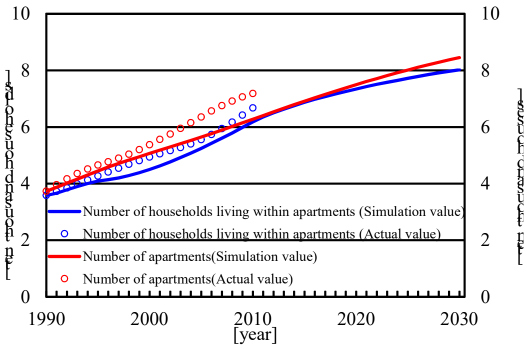

***Figure 4.** The number of the apartment houses and households that live in the apartment house*

CO_2 EMISSION CALCULATION METHOD

In this study, total CO_2 emissions (C) from the residential sector were calculated using equation 1. In this section, we describe the calculation method used to compute equation 1. Among the variables, the number of detached houses (HD) and apartments (HA) were calculated using the long-term prediction model developed as part of this study (Figures 2 and 3). First, we discuss the calculation of basic CO_2 emissions per detached house (C_{BD}) and apartment (C_{BA}). Second, we explain the calculation of PV integration rate (PR) and CO_2 emissions per household containing a PV system (C_{PV}).

$$C(i) = HA(i) \times C_{BA}(i) + HD(i) \times C_{BD}(i) - HD(i) \times PR(i) \times C_{PV}(i) \quad \cdots(1)$$

Calculation of basic CO_2 emissions per household

The basic CO_2 emissions per household were calculated using the model developed by this project for the residential sector, by multiplying energy consumption by a CO_2 emission coefficient. The CO_2 emission coefficient differed each year. Actual data of energy consumption per household and fuel rate of the residential sector were used from 1990 to 2010 (Energy Conservation Center 2013). In Japan, an energy conservation law suggests the criteria for building insulation: when a new building is built, a Q-value is used to divide the floor area by the total amount of heat loss per unit temperature of standard thermal insulation. A minimum insulation standard is proposed, which has changed three times: 1992, 1999, and 2013, since it was implemented in 1980. Table 2 shows the change in the energy conservation law used in this study. Since 2010, the energy consumption per household has to be reduced each year using the value of the energy conservation law in Table 2. Firstly, the average Q-value that relates to changes in the heating and cooling energy consumption is calculated for a new house for each standard value. Then, the rate of change of heating and cooling energy consumption each year is determined by the average Q-value using data regarding the relationship between Q-value and heating and cooling energy consumption (Land, Infrastructure and Transportation Ministry 2014). The change in energy consumption per household is shown in Figure 5. Currently, the CO_2 emission coefficient used is the actual value from 1990 to 2010 (The energy data and modeling center 2013, Ministry of the Environment 2016). Since 2010, it has been calculated as the value from 2010. The change in CO_2 emission coefficient is shown in Figure 6. The C_{BD} and C_{BA} were computed using these calculations.

Table 2. *Change in the energy conservation law used in this study (values are average Q-values by climatic region)*

Standard	*No standard*	*1980 standard*	*1992 standard*	*1999 standard*	*2013 standard*
Q-value ($W/m^2 \cdot K$)	6.2	5.6	4.1	2.5	2.5

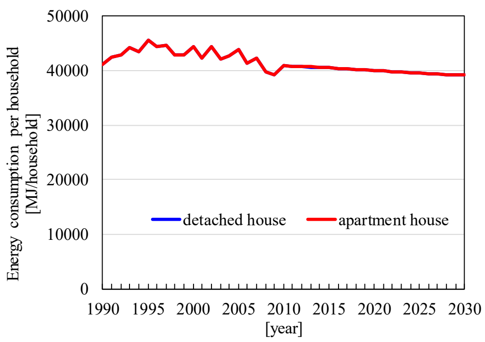

Figure 5. *Change in energy consumption per household*

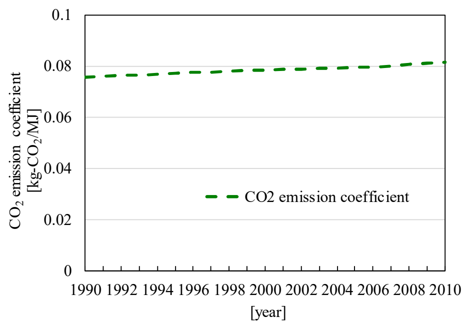

Figure 6. *Change in CO_2 emission coefficient*

Calculation of CO_2 reduction due to PV in detached houses

Here, we describe the calculation of PV integration rate and CO_2 emissions per household equipped with PV. The PV was assumed to have an applied efficiency of 12 %, a 3 kW capacity, a power generation of 1000 hours per year, and a CO_2 reduction of 1.86 t-CO_2 per household per year for detached houses (Ministry of the Environment 2001). Thus, C_{PV} was computed by subtracting 1.86 t-CO_2 from C_{BD}. The PV integration rate was calculated using equation 2. The number of relevant cases is a cumulative value of the number of cases selected each year. The number of selected cases was calculated by multiplying the PV selection rate (*SR*) by the number of detached houses available for new purchase each year. The number of detached houses available for new purchase (*N*) was calculated using equation 3.

$$PR(i) = \frac{\sum_{j=2003}^{i} N(i) \times SR(i)}{HD(i)} \qquad \cdots(2)$$

$$N(i) = HD(i) - HD(i-1) \times PR(i-1) \qquad \cdots(3)$$

The expression for calculating selection rate is shown in Figure 7. The PV selection rate was determined from the ratio of the actual number of PV cases from 2003 to 2013 to the payback period, and the selection rate was assumed as 55 % when the payback period is 5 years. (Ito et al. 2012).

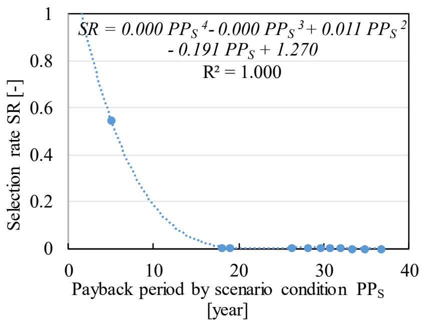

***Figure 7.** Relationship between the PV payback period under different scenario conditions and the PV selection rate*

The payback period under basic conditions is shown in equation 4. The payback period is the time required for the amount invested in an asset to be repaid by the net cash outflow generated by the asset, and the production unit cost is reduced according to the cumulative production. Equation 4 is an input variable for calculating the electricity bill (*B*).

$$PP_B(i) = \frac{PV(i)}{AP \times B(i)} \qquad \cdots(4)$$

The expected PV price was determined from the relationship between the real PV price from 1993 to 2011 and the payback period (Figure 8). Furthermore, the expected electricity charge was derived from the linear relationship between the actual electricity charge and the thermal power rate (Figure 9). In addition, the thermal power ratio used actual data from 1990 to 2015 and estimated data from 2016 to 2029, in reference to the power ratio plan for 2030.

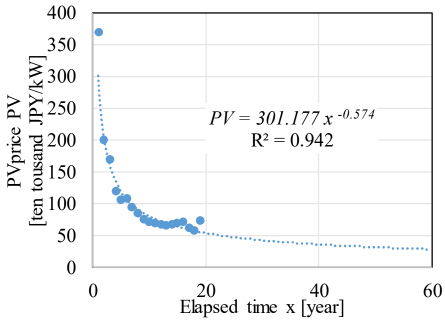

Figure 8. *Relationship between elapsed time and PV price*

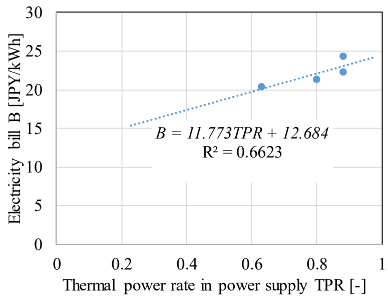

Figure 9*. Relationship between thermal power ratio and electricity bill*

SCENARIO DESCRIPTIONS

Equation 5 shows the payback period by different scenarios, including subsidies (*S*) and feed-in tariffs (*FIT*). FIT is used to prompt renewable energy use by purchasing electricity generated from renewable energy sources such as PV and wind power on a fixed-period contract at a fixed price. The scheme was started in 2012 in Japan.

$$PP_S(i) = \frac{PV(i) - S}{AP(B(i) \times SC + FIT(i) \times ES)} \quad \cdots(5)$$

Kashiwa implemented the PV subsidy scheme in 2014. The maximum PV subsidy is 30,000 JPY per kW, and the maximum subsidy was used in this study. The initial price is, therefore, reduced by the subsidy. The annual amount of power generation (*AP*), self-consumption rate (*SC*), and electricity sales rate (*ES*) were fixed to 3000 kWh, 44 % and 56 %, respectively (Ministry of Economy, Trade and Industry 2015). An expected procurement cost was approximated by the linear relationship in Figure 10, which describes the relationship between the actual procurement cost from 2012 to 2016 and the payback period under basic conditions, based on the fact that the shorter the payback period, the more the procurement cost decreases.

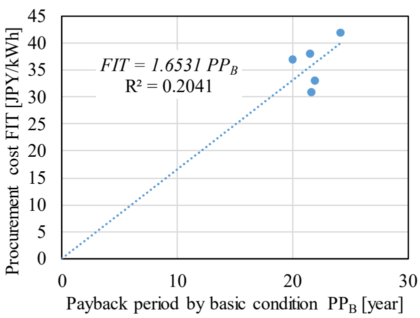

Figure 10*. Relationship between PV payback period under basic conditions and the procurement cost*

The scenarios for CO_2 emission reduction and relevant energy supply policies are shown in Table 3. The start year for each policy is the year in which the policy was implemented. In scenario 1, the FIT scheme started with PV integration from 2012; scenario 2 then maintained the current policies, with the addition of the subsidy policy, and in scenario 3, the subsidy price increased to 120,000 JPY per household from 2017. The higher subsidy price was decided with reference to the price in the city that pays the most subsidies in Japan.

Table 3. *Scenario descriptions*

Scenarios	*Overview of scenarios*
Scenario 1	- PV (from 2003) - FIT (from 2012)
Scenario 2	- PV (from 2003) - FIT (from 2012) - Subsidy (from 2014: 90,000 JPY/household)
Scenario 3	- PV (from 2003) - FIT (from 2012) - Subsidy (from 2014 to 2016: 90,000 JPY/household, from 2017 : 120,000 JPY/household)

RESULTS AND DISCUSSION

The PV integration rates for each scenario in detached house from1990 to 2030 are shown in Figure 11. The PV integration rate in the case of no policy support was added to Figure 11 to clearly compare different policy combinations. When PV was distributed without supporting policies, the PV integration rate was 4 % in 2013 and 6 % in 2030. CO_2 emissions in the residential sector are shown in Figure 12, according to each scenario. Table 4 shows the PV integration rates, CO_2 emissions, and change of rate between 2013 and 2030. When analyzing CO_2 emissions in terms of the housing type, CO_2 emissions of detached houses were reduced by from 16 % to 31 % because PV integration rates were increased according to change of the scenario conditions. CO_2 emissions of apartments were increased and there were the same values in all scenarios because PV was not adopted in apartments. When analyzed by the scenarios in the residential sector, CO_2 emissions were reduced by 4 % in 2030 compared to 2013 and the PV integration rate increased to 33 % in scenario 1. The PV integration rate in scenario 1 increased rapidly compared to the PV integration rate with no supporting policy. The payback period was reduced by approximately seven years, and selection rate increased rapidly due to the steep reduction in payback period. In scenario 2, CO_2 emissions in the residential sector were reduced by 10 % in 2030 compared to 2013, and PV integration rate increased to 50 %. The CO_2 reduction effects were 6 % higher than scenario 1 since the payback period using the subsidy policy was reduced by approximately two years. As a result, it was determined that the current subsidy policies reduce CO_2 emissions. In scenario 3, CO_2 emissions in the residential sector decreased by 12 % in 2030 compared to 2013, and PV integration rate increased to 55 %. When the subsidy was increased from scenario 2, CO_2 emissions were cut by just over 2 % more, accounting for a quarter of the 40 % reduction target for the residential sector.

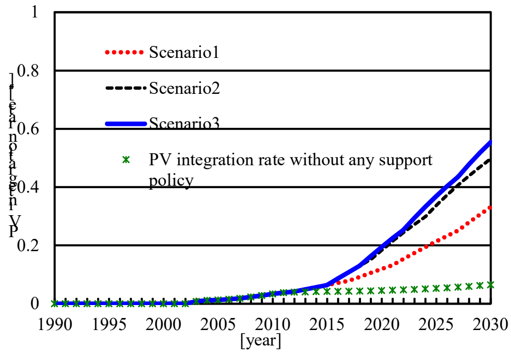

***Figure 11**. PV integration rates in detached house from1990 to 2030*

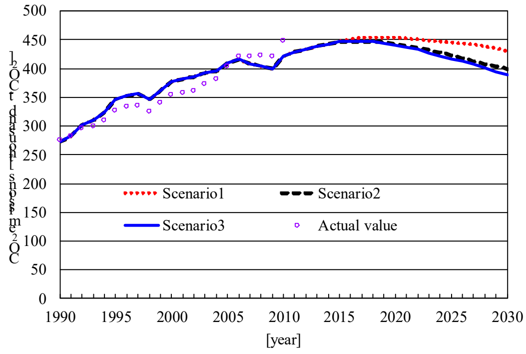

***Figure 12.** CO_2 emissions in the residential sector from1990 to 2030*

***Table 4.** FY 2030 compared to FY 2013 of CO_2 emissions, rate of change and PV integration rates in 2030*

Items	*Year*	*PV integration rate(%)*	*Residential sector*		*Detached*		*Apartment*	
			Thousand t-CO_2	*Rate of change (%)*	*Thousand t-CO_2*	*Rate of change (%)*	*Thousand t-CO_2*	*Rate of change (%)*
Scenario 1	2013	5	505	−4	289	−16	216	+13
	2030	33	486		243		244	
Scenario 2	2013	5	505	−10	289	−27	216	+13
	2030	50	455		212		244	
Scenario 3	2013	5	505	−12	289	−31	216	+13
	2030	55	445		201		244	

CONCLUSION

In this study, we present the effect of PV on reducing CO_2 emissions in the residential sector according to different supporting policies. The PV selection rate involved various assumptions, and was included in the long-term prediction model in order to examine the CO_2 reduction effect according to different PV support policies. As a result, the model predicted a reduction in CO_2 emissions of between 4 % and 12 %. Therefore, we conclude that, using the long-term prediction model constructed by the authors, it is possible to analyze the CO_2 reduction effect according to a range of supporting policies.

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