Impacts of demographic, meteorological, and economic changes on household CO_2 emissions in the 47 prefectures of Japan*

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Abstract

An understanding of the factors affecting household CO_2 emissions is necessary for effective climate policies aimed at reducing emissions. We developed an empirical model of household CO_2 emissions in the 47 prefectures of Japan and conducted a sensitivity analysis to evaluate the impacts of demographic, meteorological, and economic changes on emissions. Emissions are projected to increase with demographic changes by 2030, and to decrease with temperature increases during the 21st century. Carbon taxes on energy sources are projected have a limited effect on the reduction of emissions in the short term. The closure of nuclear power plants is projected to lead to a substantial increase in emissions.

JEL classification Q54, R21, R28

Key words Household CO_2 emissions, Japan, Global warming, Carbon tax, Nuclear energy

1 Introduction

In the Kyoto Protocol, Japan agreed to reduce national greenhouse gas emissions per year by 6% from the 1990 level (base year) during the first commitment period of 2008–2012 (United Nations 1998). However, Japan's CO_2 emissions have increased since 1990. Japan's greenhouse gas inventory (GIO 2012) indicates that the mean national CO_2 emissions for 1990–2010 were 1,221 $MtCO_2$, which exceeded the base year emissions by 80 $MtCO_2$. A large part of the increased national CO_2 emissions originated from the household sector. Mean household CO_2 emissions increased by 27 $MtCO_2$ from the base year level, while mean industrial CO_2 emissions decreased by 25 $MtCO_2$. In order to set effective policies for reducing household CO_2 emissions, we must identify the factors that affect emissions and evaluate the emission-reduction impacts of changes in determinants.

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The determinants of household emissions can be classified into three types: demographic, meteorological, and economic.

The number of households is an important demographic factor determining household CO_2 emissions. An increase in the number of households directly leads to an increase in energy demand from the household sector. The number of households in Japan has increased from 41 million in 1990 to 52 million in 2010 (MIC 2012a). The National Institute of Population and Social Security Research (NIPSSR 2009) projected that the number of household will peak around 2015 and then decrease to 49 million households by 2030. The rate of decrease is projected to be relatively slow in Okinawa and urban prefectures, which will influence the regional distribution of household CO_2 emissions.

Household CO_2 emissions are influenced by meteorological factors, particularly temperature. Using the A2 scenario of the Intergovernmental Panel on Climate Change – Special Report on Emissions Scenarios (IPCC SRES) (IPCC 2000), the Japan Meteorological Agency (JMA 2005) projected that the annual average temperature will increase by 2–3°C in all regions of Japan during the 21st century. The warming will increase energy demand for cooling and decrease energy demand for heating. The impact of warming on emissions is then determined by the sum of the increased emissions from cooling and the decreased emissions from heating.

Two economic factors, energy price and CO_2 intensity (CO_2 emissions per unit of energy consumed), are associated with two major climate policies: carbon taxation and low carbon power generation. Carbon taxation aims to decrease the demand for fossil fuels by increasing their prices according to their CO_2 intensity. That is, a higher tax is charged on an energy source with a higher CO_2 intensity. However, if household demand for energy is inelastic with respect to energy price, the short-term impact of carbon taxation on the reduction of household CO_2 emissions is limited (Baranzini et al. 2000).

Low carbon power generation aims to decrease the CO_2 intensity of electricity by decreasing the CO_2 intensity of primary energy inputs to fossil fuel power plants and by increasing the efficiency of power generation and transmission. As described in the 2010 basic energy plan (METI 2010), the Japanese government had assumed a substantial increase in nuclear power generation to achieve ambitious mid-term targets related to low carbon power generation (Duffield and Woodall 2011). However, after the crisis at the Fukushima Daiichi nuclear plant caused by the 2011 Tohoku earthquake and tsunami, the Japanese government revised the 2010 basic energy plan (ANRE 2011), and all nuclear power plants were shut down for stress testing by May 2012 (FEPC 2012b). As a result, nuclear power generation in 2011 decreased by 63% relative to 2010 levels, while fossil fuel power generation increased by 26% (FEPC 2012a). The shutdown of nuclear power plants has increased the CO_2 intensity of electricity, which will increase household CO_2 emissions.

Considering this background, we developed an empirical model of household CO_2 emissions in the 47 prefectures of Japan, and evaluated the potential impacts of the following four events on emissions: (i) changes in the number of households by 2030, (ii) temperature increases during the 21st century, (iii) carbon taxes on energy sources, and (iv) the shutdown of nuclear power plants. The impacts of these events on household emissions are measured in terms of sensitivity. The sensitivity of the emissions with respect to an event was given by the rate of change from baseline emissions to expected emissions generated by the event. The baseline and expected emissions were derived from the model.

Section 2 provides details of the tools used in the sensitivity analysis. First, household

CO_2 emissions are expressed as the product of the number of households, the CO_2 intensities of different energy sources, and energy demands per household (basic equation). Second, data regarding emissions for 1990–2007 are summarized. Third, the emission model is described using basic equations and data. Fourth, the sensitivity of emissions and different events are defined. In Section 3, the sensitivity of emissions with respect to the different events is calculated, and possible impacts of natural and social changes on emissions are discussed. Section 4 presents a conclusion. Appendices A and B describe details of the models.

2 Methods

2.1 Basic equation

Fig. 1 shows the 47 prefectures of Japan. The prefectures are identified by $p = 1, \ldots, 47$. Each prefecture has a household sector in which six energy sources are used: electricity, kerosene, propane, municipal gas, gasoline, and district heating. The energy from these sources is classified into four types $x = e, f, g, h$ (Table 1). Fiscal years are denoted by the time variable $t :=$ Year $- 1989$. All variables used in this paper depend on p and t, but the suffixes are usually not shown for simplicity.

Let $E_x(p,t)$ [GJ] be the demand for energy x in the household sector of the p-th prefecture in fiscal year t. The household CO_2 emissions $G(p,t)$ [$kgCO_2$] are defined as

$$G(p,t) := \sum_x G_x(p,t), \tag{1}$$

where $G_x(p,t)$ denotes CO_2 emissions from meeting $E_x(p,t)$. Equation (1) can be transformed into

$$G = H \sum_x S_x \bar{E}_x, \tag{2}$$

where H is the number of households, S_x [$kgCO_2$/GJ] is the CO_2 intensity of energy x, and $\bar{E}_x$ [GJ/household] is the demand for energy x per household. Equation (2) is the basic equation of household CO_2 emissions, which indicates that household CO_2 emissions consist of nine factors: $H, S_e, \ldots, S_h, \bar{E}_e, \ldots, \bar{E}_h$. The basic equation is used as the framework of the emission model.

2.2 Data

Fig. 2 shows mean emissions, CO_2 intensity, and energy demand per household in the 47 prefectures from 1990–2007. The regional distribution of household CO_2 emissions is strongly correlated with that of the number of households (Panels a and b). Regional differences in the CO_2 intensity of electricity correspond to the differences between electric power companies (EPCs) (Panel c). Japan's ten major EPCs and their areas of coverage are listed in Table 2. The demand for kerosene, propane, and municipal gas per household, which are used for heating, is relatively large in northern regions such as Hokkaido and Tohoku (Panel d). The demand per household for gasoline is relatively small in urban areas of regions such as Kansai and Kanto (nearly equal to the area covered by Tokyo EPC).

Fig. 3 shows growth rates of the emissions, CO_2 intensity, and energy demand per household in the 47 prefectures of Japan for 1990–2007 (relative to 1990 levels). The growth rate of the emissions is defined by

$$\frac{G^{\mu}(p,t) - G(p,1)}{G(p,1)} \times 100 \; [\%], \tag{3}$$

where $G^{\mu}(p,t)$ denotes the mean emissions for 1990–2007. The denominator is the emissions in 1990, and the numerator is the excess of the mean emissions for 1990–2007 over the emissions in 1990. The emissions increased by 11.3–44.6% in all prefectures between 1990 and 2007 (Panel a). In many prefectures, the number of households and the energy demand per household increased (Panels b and d), while the CO_2 intensity was maintained at the 1990 level (Panel c). Thus, the increase in the emissions can be attributed to an increase in both the number of households and energy demand per household.

2.3 Model

A model of household CO_2 emissions was obtained by substituting models of the CO_2 intensity and energy demand per household (factor models) into the basic equation (2). Table 3 lists all variables used for modeling, and Table 4 presents the factor models.

CO_2 intensity of electricity

The CO_2 intensity of electricity can be expressed as

$$S_e = \frac{w'_a S_a}{C_e}, \tag{4}$$

where w'_a is the rate of fossil fuel power generation, S_a is the CO_2 intensity of the primary energy input into a fossil fuel power plant, and C_e is the efficiency of power generation and transmission. This theoretical model is constructed as follows.

Let E_a and E_b be the inputs of primary energy into fossil fuel and non-fossil fuel power plants, respectively. Each power plant has a CO_2 intensity of S_a and S_b, respectively. Under the assumption that non-fossil fuel plants emit no CO_2 ($S_b = 0$), S_e is written as

$$S_e := \frac{G_e}{E_e} = \frac{S_a E_a + S_b E_b}{C_e(E_a + E_b)} = \frac{S_a}{C_e} \cdot \frac{E_a}{E_a + E_b}, \tag{5}$$

where C_e is defined by $E_e/(E_a + E_b)$. Let E'_a and E'_b be the outputs of electricity from fossil fuel and non-fossil fuel power plants, respectively. The efficiencies of fossil fuel and non-fossil fuel power plants can be expressed as E'_a/E_a and E'_b/E_b. Assume that fossil fuel and non-fossil fuel power plants have the same efficiency (Kainou 2009). From this assumption, we obtain $E_b = E_a E'_b/E'_a$. Using this equality,

$$\frac{E_a}{E_a + E_b} = \frac{E'_a}{E'_a + E'_b} = w'_a, \tag{6}$$

where w'_a is defined by $E'_a/(E'_a + E'_b)$. Substituting (6) into (5) gives the model (4).

Energy demands per household

The empirical models of energy demands per household have log-linear forms:

$$\log \bar{E}_e = \log \theta_1 + \theta_2 \log(D_{\mathrm{H}} + 1) + \theta_3 \log(D_{\mathrm{C}} + 1) - \theta_4 \log P_e^* - \theta_5 \exp(-\theta_6 t) + \epsilon_e, \tag{7}$$

$$\log \bar{E}_f = \log \theta_7 + \theta_8 \log(D_{\mathrm{H}} + 1) - \theta_9 \log P_f^* + \epsilon_f, \tag{8}$$

$$\log \bar{E}_g = \log \theta_{10} + \theta_{11} \log P_g^* + \theta_{12} \exp(-\theta_{13} t) + \epsilon_g, \tag{9}$$

where $\theta_1, \ldots, \theta_{13}$ are parameters and $\epsilon_e, \epsilon_f, \epsilon_g$ are random error terms. $\theta_1, \theta_7, \theta_{10}$ are positive, θ_{11} and θ_{12} are positive or non-positive, and the other parameters are non-negative. The parameters are estimated by least squares methods using the data between 1990 and 2007. If any non-negative parameter has a negative estimate, the model including the parameter is re-estimated under the assumption that the true parameter is zero.

D_{H} [°C-day] and D_{C} [°C-day] are heating and cooling degree days at the base temperature 18°C, which is defined as

$$D_{\mathrm{H}} := \frac{\sum_{i=1}^{365} \max(18 - T_{\mathrm{day}(i)}, 0)}{365}, \quad D_{\mathrm{C}} := \frac{\sum_{i=1}^{365} \max(T_{\mathrm{day}(i)} - 18, 0)}{365}, \tag{10}$$

where $T_{\mathrm{day}(i)}$ [°C] denotes the daily average temperature of the i-th day. The heating (cooling) degree day is based on the assumption that households use energy for heating (cooling) if the daily average temperature is lower (higher) than the base temperature. At the base temperature, the terms $\log(D_{\mathrm{H}} + 1)$ and $\log(D_{\mathrm{C}} + 1)$ equal zero, and the energy demand per household is independent of temperature.

P_x^* [1,000 yen/GJ] is the real price of energy x defined as

$$P_x^* := \frac{P_x}{Y}, \tag{11}$$

where P_x [1,000 yen/GJ] is the nominal price of energy x, and Y is the index of disposable income per household ($Y = 1$ for Tokyo in 2005). The real energy price reflects the fact that a household can buy twice the amount of energy if its disposable income doubles under a constant nominal price of energy. Note that P_f can be expressed as the weighted mean of nominal prices of kerosene, propane, and municipal gas. The weighting for each fossil fuel is given by the rate of the demand for the fossil fuel in the demand for energy f. The weights are fixed at the means for 1990–2007.

It may appear strange that gasoline demand per household can have a positive correlation with the real gasoline price. Model (9) is obtained by assuming that mileage per car has a negative correlation with car ownership per household and gasoline consumption per kilometer. This assumption is based on that of Karathodorou et al. (2010). Details are provided in Appendix A.

The terms containing the time variable t are S-shaped growth curves, which represent long-term increases in the ownership of home appliances and cars per household, respectively. The terms approach zero as t approaches ∞.

Other factors

The other factors were stable in all the prefectures during the period. Similarly to P_f, S_f can be expressed as the weighted mean of the CO_2 intensity for kerosene, propane, and municipal gas. The CO_2 intensities of the fossil fuels and their weightings are fixed at the means for 1990–2007. S_g is fixed at 67.02 $kgCO_2/GJ$ in accordance with the data. The term $S_h \times \bar{E}_h$ (CO_2 emissions per household from district heating) is fixed at the mean for 1990–2007.

2.4 Sensitivity and events

We used the sensitivity to evaluate the potential impacts of the following four events on household CO_2 emissions: (i) changes in the number of households by 2030, (ii) temperature increases during the 21st century, (iii) carbon taxes on energy sources, and (iv) the shutdown of nuclear power plants. The sensitivity of the emissions with respect to an event is defined as the relative change in the emissions caused by the event. That is

$$\frac{G_{\text{event}} - G_{\text{base}}}{G_{\text{base}}} \times 100\ [\%], \tag{12}$$

where G_{base} denotes baseline emissions and G_{event} denotes expected emissions due to the event. The baseline emissions were set by fixing all the explanatory variables of the emission model to the means for 1990–2007. The expected emissions were estimated by inputting the event into the emission model. Definitions of the events are given in Table 5. The controlled variables are key variables for each event, and the non-controlled variables are fixed at the means for 1990–2007.

In the first event, the projected number of households in 2030 (NIPSSR 2009) was input to the emission model.

In the second event, the mean heating and cooling degree days for 2081–2100 were input to the emission model. The future heating and cooling degree days were calculated using the projected changes in monthly average temperatures from the JMA (2005). Details are provided in Appendix B.

In the third event, the five energy sources (electricity, kerosene, propane, municipal gas, and gasoline) were taxed according to their CO_2 intensities. The nominal energy prices including carbon taxes are denoted by $P_e^\tau, P_f^\tau, P_g^\tau$ and were input to the emission model. The price of energy x inclusive of tax is expressed as

$$P_x^\tau := P_x^\mu + P_G \times S_x^\mu, \tag{13}$$

where the variables with μ are the means for 1990–2007 and P_G [1,000 yen/$kgCO_2$] is the nominal price of CO_2. The sensitivity was calculated for low and high CO_2 prices: 1 yen/$kgCO_2$ and 10 yen/$kgCO_2$, respectively. We also calculated the annual tax charge per household (ATC) for the carbon taxes. The ATC is expressed as

$$\sum_{x=e,f,g} \left(\bar{E}_x(P_x^\tau) \times P_x^\tau - \bar{E}_x(P_x^\mu) \times P_x^\mu \right), \tag{14}$$

where $\bar{E}_x(P_x)$ denotes the model estimate of energy demand per household under a given nominal price of energy. Note that the explanatory variables except the nominal energy price are fixed at the means for 1990–2007.

In the fourth event, Japan's ten EPCs (Table 2) shut down all nuclear power plants and shift from nuclear to fossil fuel power generation. The CO_2 intensity of electricity is controlled under naive and low-carbon scenarios. In the naive scenario, the EPCs were assumed to keep the CO_2 intensity of primary energy input into fossil fuel power plants at the levels for 1990–2007. w'_a increased to the rate of the total electricity generated from fossil fuel and nuclear power plants. S_a and C_e were fixed at the means for the period. In the low-carbon scenario, the EPCs were assumed to replace all fossil fuel power plants with highly efficient natural gas power plants. w'_a was the same as in the naive scenario. S_a decreased to the CO_2 intensity of natural gas (49.46 $kgCO_2/GJ$; Kainou 2009), and C_e increased to 0.45 (= 45%). In this case, the use of combined-cycle gas turbines was assumed.

3 Results and discussions

3.1 Changes in the number of households by 2030

Fig. 4 shows the sensitivity of household CO_2 emissions in the 47 prefectures of Japan with respect to changes in the number of households by 2030. Because of the demographic changes, emissions are projected to increase in 27 prefectures and to decrease in 20 prefectures. The sensitivity ranges from −12.9% in Yamaguchi to 36.3% in Okinawa. Except for Okinawa, the sensitivity has high positive values in urban prefectures: Shiga (24.2%), Tokyo (20.2%), Aichi (19.9%), Kanagawa (18.2%), and Saitama (14.3%). Japan's household CO_2 emissions are expected to increase by 5.9%.

Because a household is the minimum unit of the household sector, household CO_2 emissions are strongly associated with the number of households. As described by basic equation (2), an increase in the number of households increases household CO_2 emissions through an increase in household demand for energy. According to the NIPSSR (2007, 2009), the number of households will start to decrease in 45 prefectures by 2030 due to the long-term downward trend in population. However, the rate of decrease in the number of households is projected to be relatively slow in Okinawa and urban prefectures, where the rate of decrease in the population will be relatively slow and the number of single-person households will increase. In those prefectures, it takes several decades before the number of households declines to below the 1990–2007 level. In the medium term, therefore, emissions from Okinawa and urban prefectures will continue to exceed 1990–2007 levels. As a result, Japan's household CO_2 emissions will continue to increase to 2030.

In order to minimize or reduce the projected increase in emissions, policymakers must focus on the use of energy in single-person households. Hasegawa and Inoue (2004) reported that energy consumption per household increases as the number of individuals per household decreases. It therefore follows that the energy use of single-person households is inefficient.

3.2 Temperature increases during the 21st century

The JMA (2005) predicted that annual average temperature will increase by 2–3°C in all regions of Japan during the 21st century under the IPCC SRES A2 scenario (IPCC 2000). Because of this warming, heating (cooling) degree days are projected to decrease (increase) in all the prefectures (Appendix B). Hence, household CO_2 emissions from heating (cooling) are expected to decrease (increase).

Fig. 5 shows the sensitivity of household CO_2 emissions in the 47 prefectures of Japan with respect to the projected temperature increases. The sensitivity is negative for all the prefectures except Okinawa (4.4%). In particular, northern prefectures with high heating degree days have high negative sensitivities: Iwate (−11.5%), Aomori (−10.3%), Fukushima (−9.6%), Miyagi (−9.4%), and Hokkaido (−7.9%). Overall Japan's household CO_2 emissions are expected to decrease by 4.2% as a result of temperature increases.

The finding suggests that the increased emissions from cooling can be offset by the decreased emissions from heating. The regional differences in sensitivity can be attributed to the regional differences in the elasticity of energy demand per household due to local temperature. Fig. 6 shows the elasticity of energy demand per household with respect to heating and cooling degree days. In northern prefectures with high heating degree days, the demand for kerosene, propane, and municipal gas for heating is relatively elastic with respect to heating degree day (Panel a), while the demand for electricity used for cooling is inelastic with respect to cooling degree day (Panel b). Therefore warming should result in decreased emissions in the northern prefectures. In Okinawa with the highest cooling degree day, the demand for cooling is more temperature elastic than the demand for heating, and warming results in increased emissions.

The projected warming has an effect on the reduction of Japan's household CO_2 emissions. Note that this result assumes constant temperature elasticities for energy demands per household. As annual average temperature increases, the energy use of households in northern prefectures will approach that in southern prefectures. In the long term, the warming may increase (decrease) the temperature elasticity of household demand for cooling (heating). Lee and Chiu (2011) reported that the temperature elasticity of electricity demand in 24 OECD countries has gradually increased since 1985.

3.3 Carbon taxes on energy sources

Fig. 7 shows the sensitivity of household CO_2 emissions with respect to carbon taxes on energy sources (Panel a) and the ATCs (Panel b) for the 47 prefectures of Japan. If the nominal price of CO_2 is 1 yen/kgCO_2, 42 prefectures will have a negative sensitivity, ranging from −0.8% in Okinawa to −0.0% in Chiba, while five prefectures (Yamagata, Fukushima, Ibaraki, Tochigi, and Gunma) have a slight positive sensitivity. Therefore Japan's household CO_2 emissions are expected to decrease by 0.2%. The ATC ranges from 2,648 yen/household in Tokyo to 7,202 yen/household in Yamagata.

If the nominal price of CO_2 increases from 1 yen/kgCO_2 to 10 yen/kgCO_2, the sensitivities and ATCs increase by factors of approximately nine and ten, respectively. For 42 prefectures negative sensitivity ranges from −6.7% to −0.0%, and for five prefectures positive sensitivity ranges from 0.1% to 0.3%. Japan's household CO_2 emissions would be expected to decrease by 1.9%. The ATC ranges from 26,168 yen/household in Tokyo to 72,134 yen/household in Yamagata.

For the higher price of CO_2, annual energy expenditure per household increases by 12–22% relative to 1990–2007, but the rate of decrease in Japan's household CO_2 emissions (−1.9%) is slower than the annual average increase in the rate of emissions between 1990 and 2007 (2.2%). This result suggests that the effect of carbon taxation on emission reduction is limited in the short term. As shown in Fig. 8, energy demand per household is inelastic with respect to real energy prices in all the prefectures. The price elasticity of gasoline demand is positive for 20 prefectures, which indicates that a carbon tax on gasoline could increase the demand for gasoline (Appendix A). Household demands for energy are therefore insensitive to carbon taxes in the short term.

The ATC varies among the prefectures because of the regional differences in household energy use. For the higher priced CO_2, the standard deviation of the ATCs is 11,467 yen/household, and the maximum ATC is approximately three times as high as the minimum ATC. The ATC is relatively high in northern prefectures: Yamagata, Fukushima, Akita, Aomori, and Iwate. In these prefectures, the demand for kerosene, propane, and municipal gas used for heating is large because of the cold climate, and its price elasticity is close to zero. Therefore, households will pay high carbon taxes for heating. Naive carbon taxation, as is considered in this paper, imposes heavy tax burdens on households in cold regions with high heating degree days.

This result implies that the redistribution of the revenues from carbon taxes will have an important role in reducing emissions. Even if household CO_2 emissions are insensitive to short-term changes in energy prices, the effect of carbon taxation can be enhanced by recycling the tax revenues to the market in the form of grants for projects aimed at reducing emissions (Baranzini et al. 2000). As suggested by Berkhout et al. (2004) for the Netherlands, the Japanese government could use the tax revenues to subsidize the insulation of houses in cold regions. This may reduce the regional differences in the tax burdens.

3.4 Shutdown of nuclear power plants

Fig. 9 shows the sensitivity of household CO_2 emissions in the 47 prefectures of Japan with respect to the shutdown of nuclear power plants. Prefectures covered by the same EPC (Table 2) have similar sensitivities. In the naive scenario, the emissions increase in all the prefectures except for Okinawa (0.0%) which has no nuclear power plants. The sensitivity is substantially higher in the areas covered by the Kansai (57.0–63.3%), Kyushu (43.3–47.2%), and Shikoku EPCs (40.5–42.8%). Japan's household CO_2 emissions are expected to increase by 27.5%.

In the low carbon scenario, the sensitivity declines by 16–55% relative to the naive scenario. The sensitivity is still positive in the areas covered by the Kansai (7.6–8.4%) and Tokyo EPCs (4.4–5.5%), but is negative in the other areas. In addition to Okinawa (−41.5%), the prefectures covered by Chugoku EPC also have high negative sensitivities, ranging from −24.4% to −22.2%. Japan's household CO_2 emissions are expected to decrease by 3.0%.

The results suggest that the shift from nuclear to fossil fuel power generation substantially increases household CO_2 emissions. The impact of the energy shift is especially severe in the areas covered by EPCs with a high dependence on nuclear power generation. Between 1990 and 2007, the Kansai, Kyushu, and Shikoku EPCs generated 51.3%, 48.8%, and 46.6% of their electricity from nuclear energy, respectively (FEPC 2012c). The prefectures covered by these EPCs are sensitive to the energy shift, and their CO_2 intensities for electricity generation approximately double in the naive scenario, relative to 1990–2007.

The EPCs can reduce the increased emissions by decreasing the CO_2 intensity of the primary energy input into fossil fuel power plants. If electricity generation from renewable sources remains at the level existing in 1990–2007, the EPCs would be required to replace almost all of the fossil fuel power plants with natural gas combined-cycle plants to offset the increased emissions. However, a large increase in natural gas power generation may be expensive for the EPCs because Japan's domestic production of natural gas is very small. Japan imports more than 95% of its natural gas supply from foreign countries such as Malaysia, Australia, and Qatar (Ministry of Finance 2012). If Japan aims to decrease its dependency on nuclear energy without abandoning climate policies, a substantial increase in the use of renewable energy will be essential (Huenteler et al. 2012).

Conclusions

We have shown empirically that the sensitivity of household CO_2 emissions with respect to demographic, meteorological, and economic changes varies among the 47 prefectures of Japan. Our results suggest that the effects of climate policies aimed at reducing the emissions depend on regional characteristics.

Increases in the number of households over the medium term will increase household CO_2 emissions. The upward trend in the number of households is projected to reverse to a downward trend in most prefectures by 2030. However, the rate of decrease will be relatively slow in Okinawa and urban prefectures owing to an increase in single-person households. The emissions in those prefectures will continue to exceed 1990–2007 levels for several decades. Policymakers need to focus on reducing the energy use of single-person households to minimize or reduce the projected increase in emissions.

The projected warming in Japan will increase household demand for cooling and decrease household demand for heating. The increased emissions from cooling will be offset by the decreased emissions from heating in all the prefectures, except for Okinawa which has a large (small) demand for cooling (heating). The rate of decrease in emissions is expected to be relatively high in northern prefectures which have large (small) demands for heating (cooling).

The short-term effect of carbon taxation on emission reduction will be limited because household demands for energy sources are price inelastic in all the prefectures. The annual tax charge per household is expected to be high in cold regions. Under naive carbon taxation, households in those regions will be forced to pay high carbon taxes for heating. Policymakers need to design fair carbon taxes and to enhance their effectiveness through the redistribution of tax revenues to projects aimed at reducing emissions.

The shutdown of nuclear power plants would increase the dependence on fossil fuel power generation, which in turn would lead to a substantial increase in emissions. The impact of such an energy shift is expected to be severe in regions with a high dependence on nuclear power generation. The increased emissions could be offset by replacing current fossil fuel power plants with natural gas combined-cycle plants. However, this would require a substantial increase in the import of natural gas, which will impose financial burdens on electric power companies. Without a substantial increase in the use of renewable energy, the shutdown of nuclear power plants will have a negative impact on climate policies.

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References

Agency for Natural Resources and Energy (ANRE). 2011. Major discussion points toward the establishment of a new "Basic Energy Plan for Japan." http://www.enecho.meti.go.jp/info/committee/kihonmondai/ikenbosyu/ronten_eng.pdf

Automobile Inspection and Registration Information Association (AIRIA). 2012. Car ownership statistics. http://www.airia.or.jp/number/index.html

Baranzini A, Goldemberg J, Speck S. 2000. A future for carbon taxes. *Ecological Economics* **32**, 395–412.

Berkhout PHG, Ferrer-i-Carbonell A, Muskens JC. 2004. The ex post impact of an energy tax on household energy demand. *Energy Economics* **26**: 297–317.

Duffield JS, Woodall B. 2011. Japan's new basic energy plan. *Energy Policy* **39**, 3741–3749.

Federation of Electric Power Companies of Japan (FEPC). 2012a. Electricity generated and purchased in FY2011 (bulletin). http://www.fepc.or.jp/english/news/generated_purchased/index.html

Federation of Electric Power Companies of Japan (FEPC). 2012b. Electricity generated and purchased in June 2012 (bulletin). http://www.fepc.or.jp/english/news/generated_purchased/index.html

Federation of Electric Power Companies of Japan (FEPC). 2012c. Electricity statistics information. http://www.fepc.or.jp/english/index.html

Greenhouse Gas Inventory Office of Japan (GIO). 2012. The GHGs emissions data of Japan (1990–2010). http://www-gio.nies.go.jp/aboutghg/nir/nir-e.html

Hasegawa Y, Inoue T. 2004. Energy consumption in housing on the basis of national scale questionnaire: Study on influence of residential characteristic and dispersion of energy consumption Part 1. *Journal of environmental engineering* **583**, 23–28. http://ci.nii.ac.jp/naid/110004083872/en/

Huenteler J, Schmidt TS, Kanie N. 2012. Japan's post-Fukushima challenge – implications from the German experience on renewable energy policy. *Energy Policy* **45**, 6–11.

Intergovernmental Panel on Climate Change (IPCC). 2000. *Special Report on Emissions Scenarios. A Special Report of Working Group III of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge.

Japan Meteorological Agency (JMA). 2005. *Global Warming Projection Volume 6.* Japan Meteorological Business Support Center, Tokyo.

Japan Meteorological Agency (JMA). 2010. Weather statistics information. http://www.jma.go.jp/jma/index.html

Kainou K. 2009. Manual of comprehensive energy statistics. http://www.rieti.go.jp/users/kainou-kazunari/download/index.html

Kainou K, Agency for Natural Resources and Energy (ANRE). 2010. Energy consumption statistics by prefecture. http://www.rieti.go.jp/users/kainou-kazunari/energy/index.html

Karathodorou N, Graham DJ, Noland RB. 2010. Estimating the effect of urban density on fuel demand. *Energy Economics* **32**, 86–92.

Lee C-C, Chiu Y-B. 2011. Electricity demand elasticities and temperature: Evidence from panel smooth transition regression with instrumental variable approach. *Energy Economics* **33**, 896–902.

Ministry of Economy, Trade and Industry (METI). 2010. Basic energy plan. http://www.meti.go.jp/committee/summary/0004657/energy.pdf

Ministry of Finance. 2012. Trade statistics of Japan. http://www.customs.go.jp/toukei/info/index_e.htm

Ministry of Internal Affairs and Communications (MIC). 2012a. Census. http://www.stat.go.jp/data/kokusei/2010/index.htm

Ministry of Internal Affairs and Communications (MIC). 2012b. Family income and expenditure survey. http://www.stat.go.jp/data/kakei/index.htm

Ministry of Internal Affairs and Communications (MIC). 2012c. Retail price survey. http://www.stat.go.jp/data/kouri/index.htm

National Institute of Population and Social Security Research (NIPSSR). 2007. Population projections by prefecture: 2005–2035. http://www.ipss.go.jp/syoushika/tohkei/Mainmenu.asp

National Institute of Population and Social Security Research (NIPSSR). 2009. Household projections for Japan by prefecture: 2005–2030. http://www.ipss.go.jp/syoushika/tohkei/Mainmenu.asp

Oil Information Center (OIC). 2012. Price information. http://oil-info.ieej.or.jp/price/price.html

United Nations. 1998. Kyoto Protocol to the United Nations Framework Convention on Climate Change. http://unfccc.int/resource/docs/convkp/kpeng.pdf

Appendix A

$\bar{E}_g$ can be expressed as the product of three elements: A [cars/household] (car ownership per household), F [GJ/km] (gasoline consumption per kilometer), and M [km/car] (mileage per car). Hence,

$$\log \bar{E}_g = \log A + \log F + \log M. \tag{A1}$$

Assume that the elements of $\bar{E}_g$ follow the log-linear models:

$$\log A = \log a_1 - a_2 \log P_g^* - a_3 \exp(-a_4 t) + \epsilon_{g1}, \tag{A2}$$
$$\log F = \log b_1 - b_2 \log P_g^* + \epsilon_{g2}, \tag{A3}$$
$$\log M = \log c_1 - c_2 \log P_g^* - c_3 \log A - c_4 \log F + \epsilon_{g3}, \tag{A4}$$

where $a_1, \ldots, a_4, b_1, b_2, c_1, \ldots, c_4$ are non-negative parameters (a_1, b_1, c_1 are positive) and $\epsilon_{g1}, \epsilon_{g2}, \epsilon_{g3}$ are random error terms. Following Karathodorou et al. (2010), we assumed that M is negatively correlated with A and F. An increase in car ownership per household can decrease the mileage per car because each car is being used less within a household. A higher gasoline consumption per kilometer leads to a higher cost of driving, which discourages the use of cars.

The parameters of (A2) were estimated by nonlinear least-squares analysis using the data for 1990–2007. The parameters of (A3) and (A4) were unknown due to the lack of data regarding the response variables. As an alternative, we estimated the $F \times M$ (gasoline consumption per car). From (A3) and (A4),

$$\begin{aligned}\log(F \times M) &= \log F + \log M \\ &= \log d_1 + d_2 \log P_g^* + d_3 \exp(-a_4 t) + \epsilon_{g4},\end{aligned} \tag{A5}$$

where d_1 is positive, d_2 is positive or non-positive, and d_3 is non-negative. By replacing a_4 with its estimate for (A2), the parameters d_1, d_2, d_3 could be estimated by ordinary least-squares analysis.

Substituting (A2) and (A5) into (A1) gives the model (9). The parameter θ_{11} is written as $-a_2 - b_2 - c_2 + a_2 c_3 + b_2 c_4$, which indicates that the effect of P_g^* on $\bar{E}_g$ can be divided into the negative effect $-a_2 - b_2 - c_2$ and the positive effect $a_2 c_3 + b_2 c_4$. An increase in P_g^* decreases $\bar{E}_g$ by decreasing A, F, and M (negative effect), while the decreases in A and F increase $\bar{E}_g$ by increasing M (positive effect). If the positive effect is stronger than the negative effect, an increase in gasoline price leads to an increase in gasoline demand per household.

Appendix B

The future heating and cooling degree days were predicted as follows. First, we estimated the semi-log linear model

$$\log D_{\mathrm{H}} = e_0 - \sum_{j=1}^{12} e_j T_{\mathrm{month}(j)} + \epsilon_{\mathrm{H}}, \tag{B1}$$

where $T_{\mathrm{month}(j)}$ is the monthly average temperature (MAT) of the j-th month, $e_0, \ldots, e_{12}$ are non-negative parameters, and ϵ_{H} is a random error term. Using temperature data from 1990 to 2007 (JMA 2010), the most efficient model was selected by minimizing the Akaike information criterion. Second, the future MATs were obtained by adding projected changes in MATs between 1981–2000 and 2081–2100 (JMA 2005) to the mean MATs for

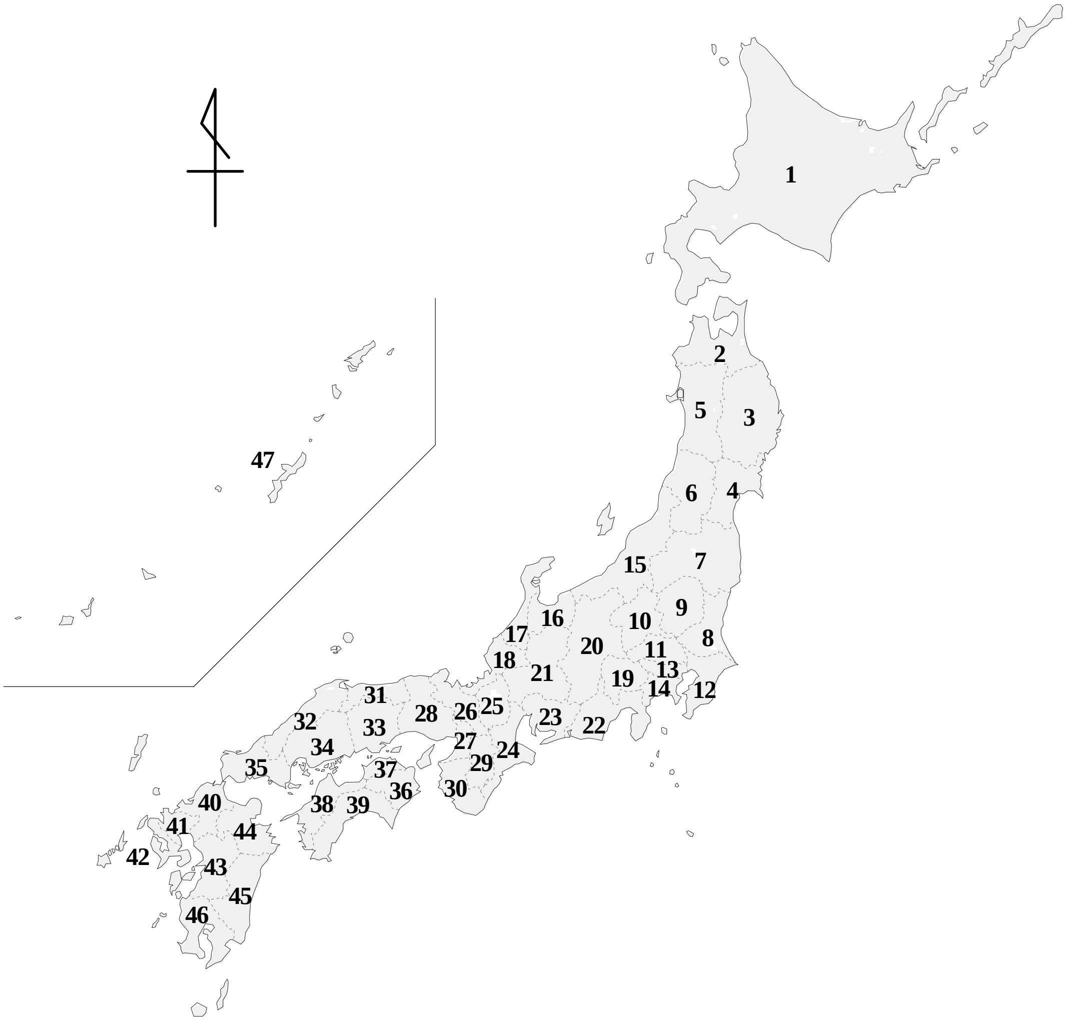
1981–2000 (JMA 2010). Third, the heating degree day was calculated by inputting the future MATs into (B1). The cooling degree day could be calculated using the equality

$$D_{\mathrm{C}} = D_{\mathrm{H}} + T_{\mathrm{year}} - 18, \tag{B2}$$

where T_{year} denotes annual average temperature. (B2) was obtained by taking the annual mean of the equality

$$\max(T_{\mathrm{day}(i)} - 18, 0) = \max(18 - T_{\mathrm{day}(i)}, 0) + T_{\mathrm{day}(i)} - 18. \tag{B3}$$

Figures



p	Prefecture	p	Prefecture	p	Prefecture	p	Prefecture
1	Hokkaido	13	Tokyo	25	Shiga	37	Kagawa
2	Aomori	14	Kanagawa	26	Kyoto	38	Ehime
3	Iwate	15	Niigata	27	Osaka	39	Kochi
4	Miyagi	16	Toyama	28	Hyogo	40	Fukuoka
5	Akita	17	Ishikawa	29	Nara	41	Saga
6	Yamagata	18	Fukui	30	Wakayama	42	Nagasaki
7	Fukushima	19	Yamanashi	31	Tottori	43	Kumamoto
8	Ibaraki	20	Nagano	32	Shimane	44	Oita
9	Tochigi	21	Gifu	33	Okayama	45	Miyazaki
10	Gunma	22	Shizuoka	34	Hiroshima	46	Kagoshima
11	Saitama	23	Aichi	35	Yamaguchi	47	Okinawa
12	Chiba	24	Mie	36	Tokushima		

Fig. 1. The 47 prefectures of Japan. Drawn by the authors. No political assertion on the territory of Japan is intended.

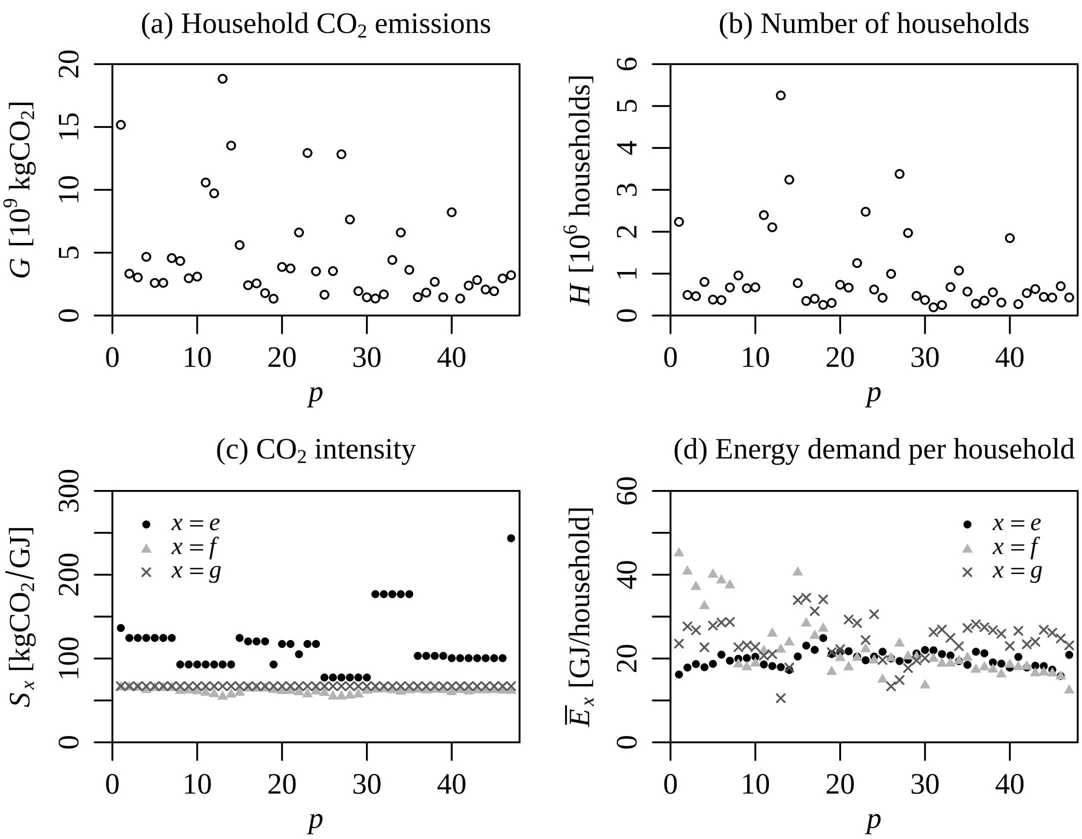


Fig. 2. Mean household CO_2 emissions, CO_2 intensity, and energy demand per household in the 47 prefectures of Japan, 1990–2007. Data relating to energy h are not shown. Calculated from Kainou and ANRE (2010) and MIC (2012a).

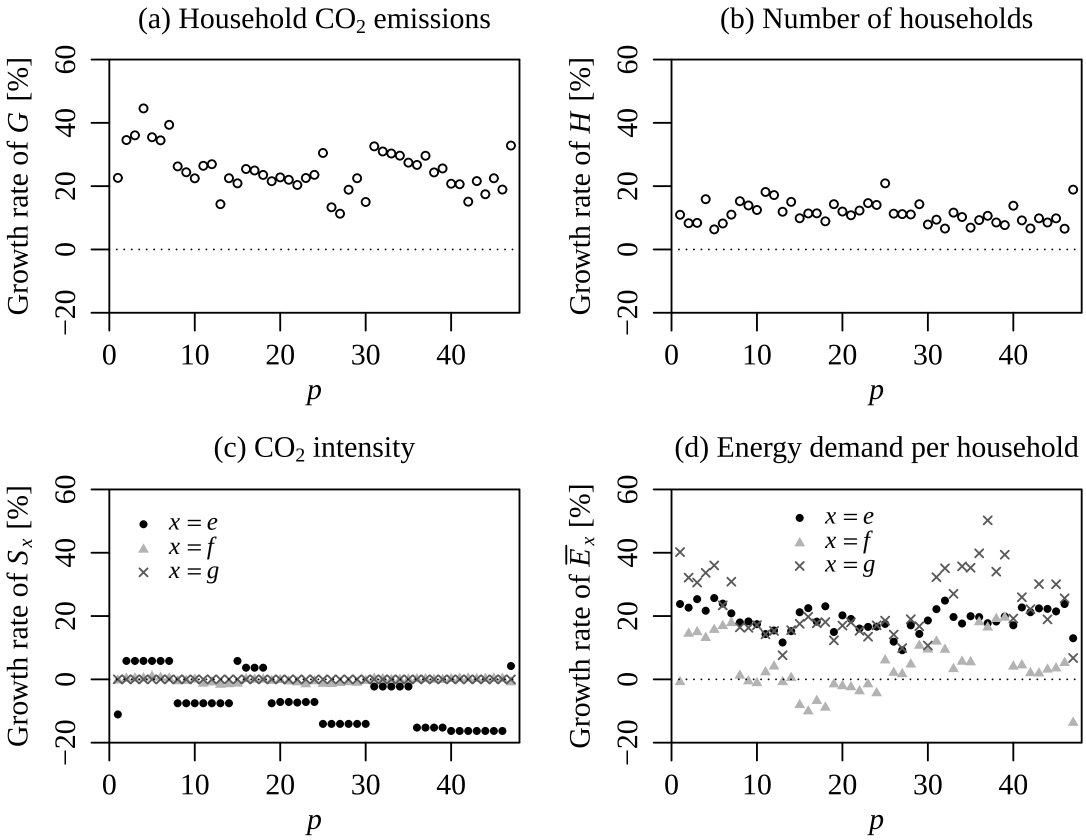


Fig. 3. Growth rates of household CO_2 emissions, CO_2 intensity, and energy demand per household in the 47 prefectures of Japan, 1990–2007 (relative to 1990 levels). Data relating to energy h are not shown. Calculated from Kainou and ANRE (2010) and MIC (2012a).

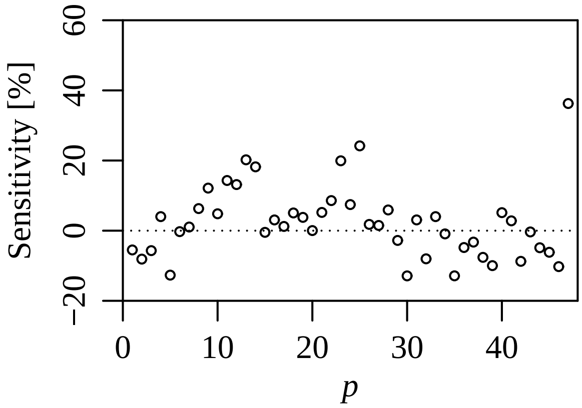


Fig. 4. Sensitivities of household CO_2 emissions in 47 prefectures of Japan with respect to changes in the number of households by 2030 (relative to 1990–2007 levels). The sensitivity of Japan's household CO_2 emissions is +5.9%.

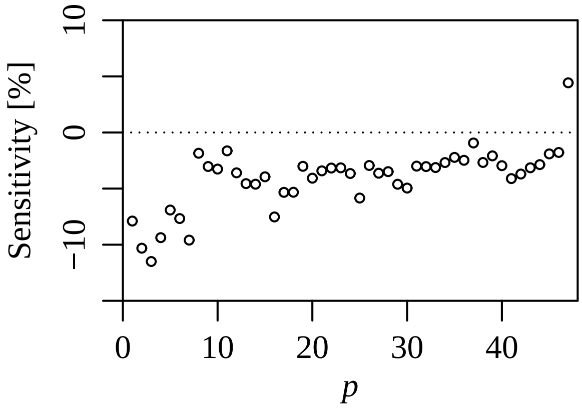


Fig. 5. Sensitivities of household CO_2 emissions in the 47 prefectures of Japan with respect to temperature increases during the 21st century (relative to 1990–2007 levels). The sensitivity of Japan's household CO_2 emissions is -4.2%.

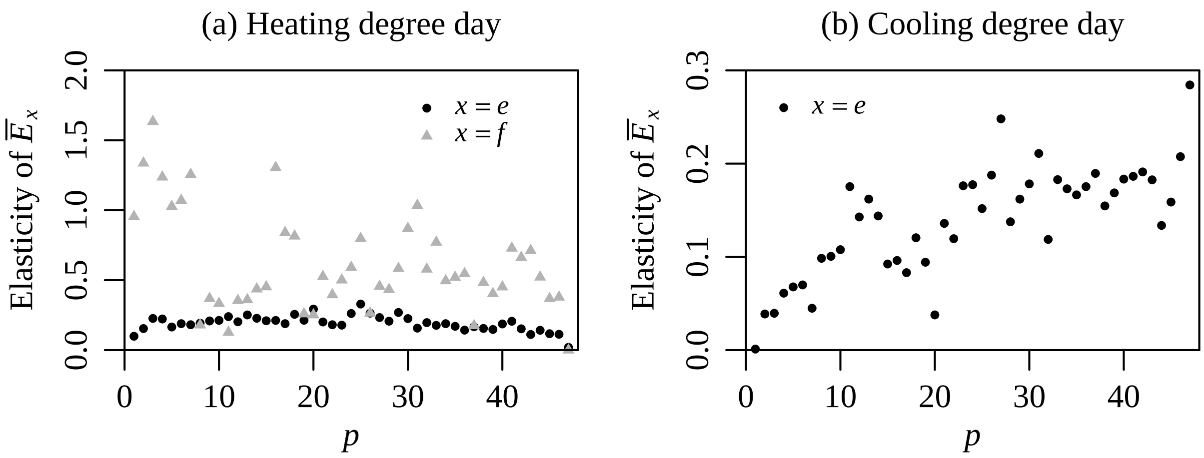


Fig. 6. Elasticities of energy demands per household in the 47 prefectures of Japan with respect to heating and cooling degree days. Elasticities with respect to $(D_\mathrm{H} + 1)$ and $(D_\mathrm{C} + 1)$.

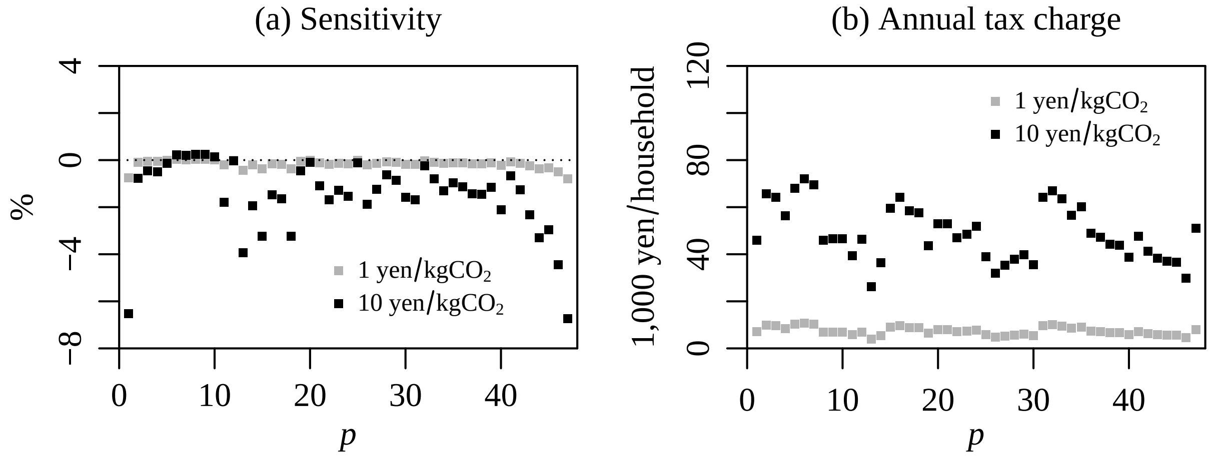


Fig. 7. Sensitivities of household CO_2 emissions with respect to carbon taxes on energy sources (relative to 1990–2007 levels) and annual tax charges per household for the 47 prefectures of Japan. Sensitivities of Japan's household CO_2 emissions in low and high CO_2 price cases are -0.2% and -1.9%, respectively.

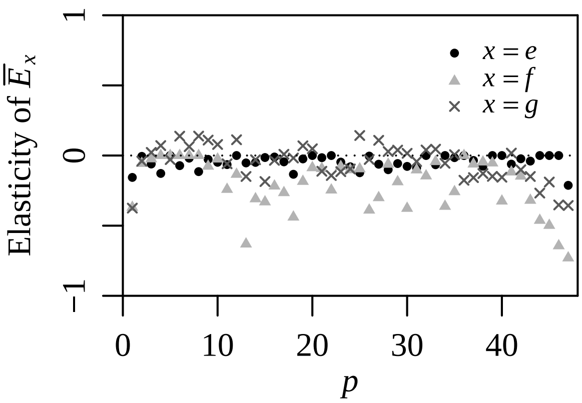


Fig. 8. Elasticities of energy demands per household in the 47 prefectures of Japan with respect to real energy prices.

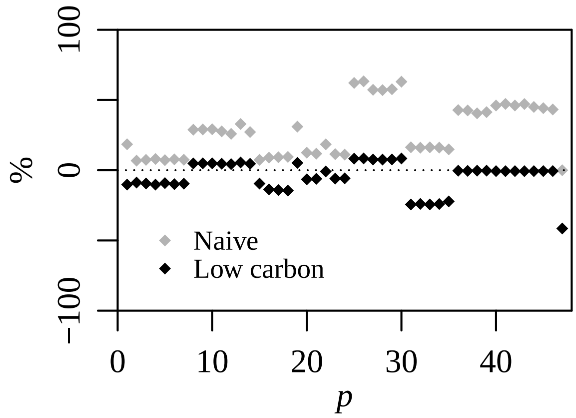


Fig. 9. Sensitivities of household CO_2 emissions in the 47 prefectures of Japan with respect to the shutdown of nuclear power plants (relative to 1990–2007 levels). Sensitivities of Japan's household CO_2 emissions in naive and low carbon scenarios are +27.5% and −3.0%, respectively.

Tables

Table 1. Classification of energy used in the household sector of Japan. Energy f is the total energy from kerosene, propane, and municipal gas.

Energy type (x)	Energy sources
e	Electricity
f	Kerosene, propane, municipal gas
g	Gasoline
h	District heating

Table 2. Ten electric power companies (EPCs) of Japan. Shizuoka ($p = 22$) is covered by both the Tokyo and Chubu EPCs.

EPC	Prefectures (p)	EPC	Prefectures (p)
Hokkaido	1	Kansai	25, 26, 27, 28, 29, 30
Tohoku	2, 3, 4, 5, 6, 7, 15	Chugoku	31, 32, 33, 34, 35
Tokyo	8, 9, 10, 11, 12, 13, 14, 19, 22	Shikoku	36, 37, 38, 39
Hokuriku	16, 17, 18	Kyushu	40, 41, 42, 43, 44, 45, 46
Chubu	20, 21, 22, 23, 24	Okinawa	47

Table 3. Variables used in the modeling of household CO_2 emissions.

Symbol	Unit	Variable	Data
G	$kgCO_2$	Household CO_2 emissions	Given by $\sum_x G_x$
G_x	$kgCO_2$	Household CO_2 emissions from consumption of energy x	Kainou and ANRE (2010)
H	households	Number of households	Estimated from MIC (2012a)
S_x	$kgCO_2$/GJ	CO_2 intensity of energy x	Given by G_x/E_x
E_x	GJ	Household demand for energy x	Kainou and ANRE (2010)
$\bar{E}_x$	GJ/household	Demand for energy x per household	Given by E_x/H
w'_a	–	Rate of fossil fuel power generation	Given by $E'_a/(E'_a + E'_b)$
S_a	$kgCO_2$/GJ	CO_2 intensity of the primary energy input into a fossil fuel power plant	Given by $S_e C_e / w'_a$
C_e	–	Efficiency of power generation and transmission	Kainou and ANRE (2010)
E_a (E_b)	GJ	Input of primary energy into fossil fuel (non-fossil fuel) power plants	–
E'_a (E'_b)	GJ	Output of electricity from fossil fuel (non-fossil fuel) power plants	FEPC (2012c)
D_{H}	°C-day	Heating degree day at the base temperature 18°C	Given by $\sum_{i=1}^{365} \max(18 - T_{\mathrm{day}(i)}, 0)/365$
D_{C}	°C-day	Cooling degree day at the base temperature 18°C	Given by $\sum_{i=1}^{365} \max(T_{\mathrm{day}(i)} - 18, 0)/365$
$T_{\mathrm{day}(i)}$	°C	Daily average temperature of the i-th day	JMA (2010)
P_x	1,000 yen/GJ	Nominal price of energy x	FEPC (2012c), MIC (2012c), OIC (2012)
Y	–	Index of disposable income per household ($Y = 1$ for Tokyo in 2005)	MIC (2012b)
P^*_x	1,000 yen/GJ	Real price of energy x	Given by P_x/Y
t	–	Time variable	Given by Year – 1989
A	cars/household	Car ownership per household	Derived from AIRIA (2012)
F	GJ/km	Gasoline consumption per kilometer	–
M	km/car	Mileage per car	–

Table 4. Models of CO_2 intensities and energy demands per household. NLS: nonlinear least squares; OLS: ordinary least squares.

Response variable	Model	Estimation methods	Explanatory variables
S_e	Theoretical model	–	w'_a, S_a, C_e
$\bar{E}_e$	Log linear model with an S-shaped growth curve	NLS	D_{H}, D_{C}, P^*_e, t
S_f	Weighted mean of CO_2 intensities of kerosene, propane, and municipal gas	–	–
$\bar{E}_f$	Log linear model	OLS	D_{H}, P^*_f
S_g	Constant (67.02 $kgCO_2/GJ$)	–	–
$\bar{E}_g$	Log linear model with an S-shaped growth curve	NLS, OLS	P^*_g, t
$S_h \times \bar{E}_h$	Mean, 1990–2007	–	–

Table 5. Definitions of events used for sensitivity analysis. Non-controlled variables are fixed at their mean values for 1990–2007.

Event	Controlled variables	Conditions
Changes in the number of households by 2030	H	Projected number of households for 2030 by the NIPSSR (2009)
Temperature increases during the 21st century	D_{H}, D_{C}	Means of heating and cooling degree days for 2081–2100 estimated by the authors, based on the projected changes in surface temperature by the JMA (2005)
Carbon taxes on energy sources (low CO_2 price case: 1 yen/kgCO_2)	P_e, P_f, P_g	Means of nominal energy prices including taxes according to CO_2 intensities of energy sources, 1990–2007
Carbon taxes on energy sources (high CO_2 price case: 10 yen/kgCO_2)	P_e, P_f, P_g	Same as in the low CO_2 price case, except for the price of CO_2
Shutdown of nuclear power plants (naive scenario)	w'_a	Mean of the rate of electricity generated in fossil fuel and nuclear power plants, 1990–2007
Shutdown of nuclear power plants (low carbon scenario)	w'_a, S_a, C_e	w'_a: Same as in the naive scenario S_a: CO_2 intensity of natural gas (49.46 kgCO_2/GJ; Kainou 2009) C_e: 0.45 (= 45%)