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The role of technology, product lifetime, and energy efficiency in climate mitigation: A case study of air conditioners in Japan

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ABSTRACT

This study analyzed the impact on the life-cycle CO_2 emissions derived from a specific durable good (i.e., household air conditioners in this study) of industrial technology changes, product lifetime changes, and energy efficiency improvements. I proposed a comprehensive structural decomposition analysis including two factors of average lifetime and energy efficiency trend of household air conditioners and applied the decomposition method to the Japanese environmental input-output tables of 1990, 1995, 2000, and 2005. The empirical results show that "Household air-conditioner sector" itself contributed to reducing life-cycle CO_2 emissions derived from household air conditioners, while other sectors such as "On-site power generation sector" and "Retail trade sector" contributed to increasing life-cycle CO_2 emissions derived from household air conditioners. I also conducted combined scenario analysis about reduction potential of product lifetime and energy efficiency of air conditioners and the results showed the reduction rate of energy efficiency necessary for maintain CO_2 emissions in 2005 at 1990 level on each average lifetime scenario. (e.g. if average lifetime of air conditioners is shortened by 1 year, energy efficiency of air conditioners have to be further improved by 20.6% from current level.

1. Introduction

In 2015, at the 21st Session of the Conference of the Parties to the United Nations Framework Convention on Climate Change (COP21), the Paris Agreement was adopted as a new international framework for tackling the global warming, taking the place of the Kyoto Protocol (United Nations Framework Convention on Climate Change, 2016). As part of this agreement, it was decided to try to hold the global average temperature to within 2 °C above the pre-industrial level, to propose and renew reduction targets every 5 years for all countries, including the major emitting countries, and to incorporate a framework for considering initiatives to help all countries achieve their reduction targets (United Nations Framework Convention on Climate Change, 2016). Thus, the agreement demonstrated a clear resolve by the whole of the international community to seriously tackle global warming. It is a clear statement that reducing emissions of CO_2, the major cause of global warming, is becoming increasingly urgent, and that measures to combat the problem must now be rapidly worked out.

Climate policies can be approached from a wide variety of viewpoints, but the lifestyles and behavior patterns of consumers are considered an important factor in terms of global warming impact (International Panel on Climate Change, 2014). In particular, since durable goods such as automobiles and air conditioners are so essential to our lifestyles, the CO_2 emitted by their manufacture and use makes a large contribution to global warming, and many previous studies have used a variety of techniques and approaches to quantitatively assess the energy use and CO_2 emissions attributable to durable goods (Yokota et al., 2003; Kagawa et al., 2006, 2008, 2009, 2011; Isaac and van Vuuren, 2009; Yan and Crookes, 2009; Pauliuk et al., 2012; Scown et al., 2013; Alberini and Bigano, 2015; Nishijima, 2016). For example, Pauliuk et al. (2012) estimated the impact on CO_2 emissions derived from passenger vehicles in China of various parameters such as population changes, vehicle travel distance reductions, fuel efficiency improvements, and vehicle lifetime changes, analyzing the potential of each of these factors for reducing emissions. Kagawa et al. (2009) estimated the impacts of product lifetime extension of automobiles on income and energy consumption in Japan with a social accounting method.

Due to two limitations, however, these previous studies were unable to identify more effective policies. The first is that the variation in energy efficiency of the durable goods over time was scarcely modelled (Nishijima, 2016). The second limitation was that the studies did not examine the potential for reducing emissions derived from not only energy efficiency changes of durable goods but the technological

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changes of all industries related to the life-cycle of the durable goods.

Motivated to redress these shortcomings, in this study I focused on sales of new household air conditioners in Japan between 1972 and 2005 and estimated the impact on the life-cycle CO_2 emissions derived from a specific durable good (i.e., household air conditioners in this study) of industrial technology changes, product lifetime changes, and energy efficiency improvements. In doing so, I proposed a comprehensive structural decomposition analysis including two factors of average lifetime and energy efficiency trend of household air conditioners and applied the decomposition method to the Japanese environmental input-output tables of 1990, 1995, 2000, and 2005. From the results, I examined the roles that the technology, lifetime, and energy efficiency of household air conditioners have played in global warming, and also proposed concrete policy options for the government and air conditioning industry regarding demand- and technology-related initiatives for reducing CO_2 emissions.

The remainder of this paper is organized as follows: Section 2 explains the methodology, Section 3 describes the data, Section 4 presents the results, and finally Section 5 offers a conclusion.

2. Methodology

2.1. Estimating the number of new residential air conditioners sold

Following the method employed in earlier studies (e.g., Kagawa et al., 2006, 2011; Nakamura et al., 2014; Oguchi and Fuse, 2015), I assumed that the proportion of new household air conditioners sold in year i still in use in year t, φ_{t-i}, follows a Weibull cumulative distribution function,

$$\varphi_{t-i} = \exp\left\{-\left(\frac{t-i}{\alpha}\right)^{\beta}\right\} \qquad (t \ge i) \tag{1}$$

where α and β are respectively scale and shape parameters (e.g., McCool, 2012). Note that when $t = i$, Eq. (1) gives the proportion of the new household air conditioners sold in year i that remain in use in year i as 1. The mean μ of the Weibull cumulative distribution function is estimated from

$$\mu = \alpha\Gamma\left(1 + \frac{1}{\beta}\right) \tag{2}$$

where $\Gamma(m)$ is the gamma function, which can be expressed as $\Gamma(m) = \int_0^\infty e^{-a}a^{m-1}da$. In this study, I initially set the values of the parameters α and β of the Weibull cumulative distribution function for household air conditioners to 7.9 and 1.8, respectively, on the basis of data from a research report by the Ministry of the Environment of Japan (2011). Therefore, using the above-adopted values for the scale and shape parameters, the average lifetime of household air conditioners, as a baseline, is $\bar{\mu} = 12.6$ years. Note that, in accordance with Kagawa et al., (2006, 2009, 2011), other values of average lifetime μ are handled by keeping the shape parameter β fixed at 1.8 and estimating the value of α by using Eq. (2).

Thus, if we assume that all the new household air conditioners sold during the period under consideration follow a Weibull cumulative distribution function with a average lifetime value $\bar{\mu} = 12.6$, then the number of household air conditioners in use that were sold as new during the period from year i to year t, $S_t(\bar{\mu})$, can be estimated using the following equation as in Nishijima (2016):

$$S_t(\bar{\mu}) = B_t(\bar{\mu}) + \sum_{i=1}^{t-1}\varphi_{t-i}(\bar{\mu})B_i(\bar{\mu}) \tag{3}$$

where $S_t(\bar{\mu})$, $B_i(\bar{\mu})$, and $\varphi_{t-i}(\bar{\mu})$ represent the number of household air conditioners in use, the number of new household air conditioners sold, and the proportion of household air conditioners still in use, respectively, when the average lifetime $\bar{\mu}$ is 12.6 years.

Using the values published by the Japan Refrigeration and Air Conditioning Industry Association (The Japan Refrigeration an Air Conditioning Industry Association) for the 33-year period from 1972 to 2005 for the number of new household air conditioners shipped each year in Japan as $B_i(\mu)$ (i = 1972, 1973, …, 2005), the number of household air conditioners in use each year for the assumed baseline average lifetime ($\bar{\mu} = 12.6$), $S_t(\bar{\mu})$, can be estimated by the following set of equations.

$$\begin{cases} S_{1972}(\bar{\mu}) = B_{1972}(\bar{\mu}) \\ S_{1973}(\bar{\mu}) = B_{1973}(\bar{\mu}) + \varphi_1(\bar{\mu})B_{1972}(\bar{\mu}) \\ S_{1974}(\bar{\mu}) = B_{1974}(\bar{\mu}) + \varphi_1(\bar{\mu})B_{1973}(\bar{\mu}) + \varphi_2(\bar{\mu})B_{1972}(\bar{\mu}) \\ \vdots \\ S_{2005}(\bar{\mu}) = B_{2005}(\bar{\mu}) + \varphi_1(\bar{\mu})B_{2004}(\bar{\mu}) + \varphi_2(\bar{\mu})B_{2003}(\bar{\mu}) + \cdots + \varphi_{33}(\bar{\mu})B_{1972}(\bar{\mu}) \end{cases} \tag{4}$$

It should be noted here that it is assumed that all the air conditioners follow the same lifetime distribution regardless of their year of manufacture.

For the sake of analysis, in this study it is assumed that the number of household air conditioners in use each year $S_t(\bar{\mu})$ as determined by Eq. (4) is invariable, irrespective of a change in average lifetime. Along with this assumption, if the proportion of air conditioners still in use changes from $\varphi_{t-i}(\bar{\mu})$ to $\varphi_{t-i}(\mu^*)$ when the average lifetime of household air conditioners changes from $\bar{\mu} = 12.6$ to μ^*, then the number of new household air conditioners sold each year over the 33-year period from 1972 to 2005, $B_i(\mu^*)$ (i = 1972, 1973, … , 2005), can be estimated sequentially as follows:

$$\begin{cases} B_{1972}(\mu^*) = S_{1972}(\mu^*) = S_{1972}(\bar{\mu}) \\ B_{1973}(\mu^*) = S_{1973}(\bar{\mu}) - \varphi_1(\mu^*)B_{1972}(\mu^*) \\ B_{1974}(\mu^*) = S_{1974}(\bar{\mu}) - \varphi_1(\mu^*)B_{1973}(\mu^*) - \varphi_2(\mu^*)B_{1972}(\mu^*) \\ \vdots \\ B_{2005}(\mu^*) = S_{2005}(\bar{\mu}) - \varphi_1(\mu^*)B_{2004}(\mu^*) - \varphi_2(\mu^*)B_{2003}(\mu^*) - \cdots - \varphi_{33}(\mu^*)B_{1972}(\mu^*) \end{cases} \tag{5}$$

Here, the first line of Eq. (5), $B_{1972}(\mu^*) = S_{1972}(\mu^*) = S_{1972}(\bar{\mu})$, indicates that regardless of a change in average lifetime, the number of new household air conditioners sold in the first year is the same as the number of air conditioners still in use in that same year. As mentioned above, since I treat the shape parameter β as fixed and re-estimate the value of α to match the new average lifetime μ^*, I can plug these parameters into Eq. (1) to determine the new value for the proportion of air conditioners still in use, $\varphi_{t-i}(\mu^*)$.

2.2. Household air conditioner energy efficiency and its time series trend

In terms of estimating the impact on CO_2 emissions associated with household air conditioners, another important factor (in addition to change in product lifetime) is change in energy efficiency (i.e., annual electricity consumption). To assess the impact on CO_2 emissions of changes in air conditioner electricity consumption, I assume in this study that the annual electricity consumption per air conditioner unit manufactured in year i, λ_i, follows a reverse logistic function,

$$\lambda_i = K\{1 + \exp(a - b \times i)\} \tag{6}$$

where K is the critical value, and a and b are parameters, with $b > 0$. The reverse logistic function is a decreasing function with respect to i, with the characteristic that as i approaches infinity, λ_i converges towards K.

Nishijima (2016) made use of annual electricity consumption data for 'average' household air conditioners (sufficient to cool a room of approximately 18 m^2) manufactured between 1995 and 2013 from a government "Energy-saving Performance Catalog" (Agency for natural resources and Energy of Japan, 2010, 2011, 2012, 2013, 2014) to estimate the reverse logistic function, obtaining the highest coefficient of determination ($R^2 = 0.966$) when $\hat{K} = 824$, $\hat{a} = -0.166$, and $\hat{b} = 0.197$. I adopted these same values for this study.

The estimated value $\hat{K}$ can be considered a critical electricity