Journal of Environmental Management 181 (2016) 582–589

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Product lifetime, energy efficiency and climate change: A case study of air conditioners in Japan

Daisuke Nishijima

Faculty of Economics, Kyushu University, 6-19-1 Hakozaki, Higashi-ku, Fukuoka, 812-8581, Japan

ARTICLE INFO

Article history:
Received 7 February 2016
Received in revised form
1 July 2016
Accepted 3 July 2016

Keywords:
Product lifetime
Life-cycle CO_2
Limit energy efficiency
Weibull distribution
Reverse logistic curve

ABSTRACT

This study proposed a modelling technique for estimating life-cycle CO_2 emissions of durable goods by considering changes in product lifetime and energy efficiency. The stock and flow of durable goods was modelled by Weibull lifetime distributions and the trend in annual energy efficiency (i.e., annual electricity consumption) of an "average" durable good was formulated as a reverse logistic curve including a technologically critical value (i.e., limit energy efficiency) with respect to time. I found that when the average product lifetime is reduced, there is a trade-off between the reduction in emissions during product use (use phase), due to the additional purchases of new, more energy-efficient air conditioners, and the increase in emissions arising from the additional production of new air conditioners stimulated by the reduction of the average product lifetime. A scenario analysis focused on residential air conditioners in Japan during 1972–2013 showed that for a reduction of average lifetime of 1 year, if the air conditioner energy efficiency limit can be improved by 1.4% from the estimated current efficiency level, then CO_2 emissions can be reduced by approximately the same amount as for an extension of average product lifetime of 1 year.

1. Introduction

After the United Nations Framework Convention on Climate Change was adopted in 1992, with the aim of stabilizing the concentration of greenhouse gases in the atmosphere, a worldwide effort began to combat global warming. When the Kyoto Protocol came into force in 2005, Japan was obligated to reduce its greenhouse gas emissions by 6% relative to their 1990 level. As a result of the various initiatives Japan took toward meeting this target, it managed to reduce emissions by 8.2% (Ministry of the Environment of Japan, 2014a,b). However, if forest absorption and emissions trading are excluded, Japan's total CO_2 emissions have risen steadily since 2009 (Ministry of the Environment of Statistics Bureau of Japan, 2015). The residential sector accounted for a substantial proportion of total emissions—16.3% in 2013 (Ministry of the Environment of Statistics Bureau of Japan, 2015)—so the reduction of total residential CO_2 emissions appears to be an urgent challenge for Japan.

Based on residential sector electricity use in 2009, after refrigerators, lights, and televisions, residential air conditioners are the fourth largest source of consumption, which also means that they are a major source of CO_2 emissions (Agency for Natural Resources and Energy, Japan, 2010b). The energy efficiency of residential air conditioners has greatly improved in recent years as a result of the increased efficiency of compressors and heat exchangers, together with the adoption of inverter technology. A comparison of air conditioners with an energy efficiency of 2.8 kW (sufficient to cool a room of approx. 18 m^2) reveals that a typical model made in 2013 consumes about 40% less energy than does one made in 1995. More recently, however, the energy efficiencies of air conditioners have improved only marginally, as their technology approaches its limits (Agency for Natural Resources and Energy, Japan, 2010, 2011, 2012, 2013, 2014).

Even as efforts to improve the energy efficiency of residential air conditioners face technological limitations, the reduction of CO_2 emissions remains an urgent task. In addition, the environmental concerns of consumers continue to mount. Nevertheless, because replacement purchases of new air conditioners do not promise any significant gains in energy efficiency, from both economic and environmental viewpoints, consumers have an incentive to continue using their current air conditioners for a longer time. This results in fewer replacement purchases of new air conditioners and a smaller quantity of CO_2 emissions generated in the production

---

E-mail address: nishijindaiko@gmail.com.

http://dx.doi.org/10.1016/j.jenvman.2016.07.010

phase of residential air conditioners. On the other hand, when old air conditioners are retained for a longer time, replacement purchases of new higher efficiency models are delayed, resulting in higher CO_2 emissions in the use phase. Thus, in considering how a longer use of residential air conditioners affects CO_2 emissions, there is a trade-off between CO_2 emissions arising from the production phase and those arising from the use phase. The answers to two questions are not entirely clear here. First, to what degree does extending the lifetime of residential air conditioners contribute to reducing CO_2 emissions? Second, to what degree does the diminishing rise in the energy efficiency of residential air conditioners hold back the reduction of CO_2 emissions that occurs when the lifetime of air conditioners becomes shorter (by accelerating new replacement purchases)?

In this study, I used a Weibull distribution model to estimate the total stock of residential air conditioners between 1990 and 2013 in order to compute the total life-cycle CO_2 emissions (sum of production-phase and use-phase emissions) associated with residential air conditioners for this period. In addition, I modelled the trend in annual energy efficiency (i.e., annual electricity consumption) of an "average" air conditioner sufficient to cool a room of approximately 18 m^2 as a reverse logistic curve with respect to time, and from the estimated parameters of the reverse logistic curve, I determined the technologically critical (limit) value of energy efficiency. Using the results of this estimation, I conducted scenario analyses to assess how changes in the average lifetime of residential air conditioners influence life-cycle CO_2 emissions in order to investigate how changes in product lifetime and energy efficiency impact the environment. It should be noted that since life-cycle CO_2 emissions associated with an end-of-life household air conditioner are negligibly small (Nakamura and Kondo, 2006), this study did not consider the end-of-life phase in the proposed analysis framework.

The rest of this paper is organized as follows: Section 2 provides a literature review; Section 3 formulates the methodology developed in this study; Section 4 presents the empirical results and discussion; Section 5 presents our conclusions.

2. Prior works

Previous studies have analyzed the environmental impacts of durable goods such as motor vehicles, buildings, and heating and cooling systems (Ou et al., 2010; Melaina and Webster, 2011; Pauliuk et al., 2012; Cellura et al., 2013; 2014; Beccali et al., 2013, ; 2014; in press; Finocchiaro et al., in press). For example, Melaina and Webster (2011) developed a formula for estimating greenhouse gas emissions from motor vehicle travel, utilizing CO_2 emissions per unit of travel distance, fuel consumption, and fuel carbon intensity, and conducted a scenario analysis aimed at achieving the greenhouse gas emission target set by the U.S. government for the year 2050. Beccali et al. (2013) conducted a comprehensive life-cycle assessment of a single-family house and estimated the energy consumptions associated with the building life-cycle and the energy benefits of retrofit actions.

Although there are many factors that conceivably influence the environmental burdens associated with durable goods, one of the most important is product lifetime. Numerous studies have analyzed the role of product lifetime on the environment and resource use (Van Schaik and Reuter, 2004; Müller, 2006; Kagawa et al., 2006, 2008, 2009, 2013, 2015). Van Schaik and Reuter (2004) not only expressed lifetime as a Weibull distribution but also developed quantitative formulae for motor vehicle weight and the constituents of the resources included in vehicles. Utilizing an integrated model for these, Van Schaik and Reuter (2004) presented a scenario analysis to investigate changes in the quantity of resources recovered from end-of-life vehicles and in the recycling rate. Kagawa et al. (2008) quantitatively analyzed the degree to which extending the lifetime of passenger vehicles reduces the energy consumption arising from passenger vehicles and gasoline. As the above-mentioned literature shows, product lifetime plays an important role in estimating the environmental impact associated with durable goods. Accordingly, some studies have attempted to estimate the survival function, which expresses the trend in lifetime, to determine average lifetime (Cohen and Whitten, 1988; Babbitt et al., 2009; Murakami et al., 2010; Oguchi et al., 2010; Kagawa et al., 2011; Oguchi and Fuse, 2015).

There have also been studies on the environmental burden associated with residential air conditioners, as a typical durable good (Sailor and Pavlova, 2003; Kondo and Nakamura, 2004; Nakamura and Kondo, 2006; Isaac and Van Vuuren, 2009; Rapson, 2014). Nakamura and Kondo (2004) used a waste input-output model to analyze how changes to the 2002 performance level of residential air conditioners impacted life-cycle emissions and life-cycle cost. They also compared the life-cycle cost when a carbon tax and discount rate are applied. Isaac and Van Vuuren (2009) estimated future energy demand for heating and cooling on the basis of assumptions of temperature increases due to global warming and showed that energy demand for air conditioners would increase sharply between 2000 and 2100. These studies on air conditioners did not estimate changes in demand for future replacement purchases of air conditioners as a result of a reduction or extension of air conditioner lifetime.

Yokota et al. (2003) assumed that the lifetime distribution of residential air conditioners followed a gamma distribution in estimating total life-cycle CO_2 emissions of residential air conditioners in Japan for the period from 1990 to 2010, including emissions during manufacturing, use, and waste disposal. Furthermore, they examined the degree to which changes in the average lifetime of residential air conditioners and changes in the recovery rate of refrigerant at the time of waste disposal impacted life-cycle CO_2 emissions. The following points, however, were not analyzed. First, trends in the energy efficiency of residential air conditioners were not modelled and empirically analyzed. Second, the impact on life-cycle environmental load in the case that the average lifetime and energy efficiency both change at the same time was not considered.

Therefore, the present study proposes an integrated model that simultaneously considers both the lifetime of residential air conditioners and their energy efficiency (electricity consumption), employing a survival function for residential air conditioners and a reverse logistic function that models the trend in air conditioner energy efficiency. This integrated model is then used to analyze the influence of lifetime and energy efficiency on life-cycle CO_2 emissions. The study covers the period from 2000 to 2013.

3. Methodology

3.1. Estimating the stock of residential air conditioners

The stock of residential air conditioners $S(t)$ in year t can be estimated using the following equation:

$$S(t) = B(t) + \sum_{i=1}^{t-1} \varphi(t-i)B(i) \quad (1)$$

where $B(t)$ ($B(i)$) is the number of newly sold residential air conditioners in year t (i), and $\varphi(t-i)$ is the survival rate in year t of the air conditioners newly sold in year i. In this study, the survival rate $\varphi(t-i)$ is assumed to follow a Weibull distribution, as follows: