CO2 Reduction Potential of Consumer Durables : A Case Study of Air Conditioners in Japan

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CO_2 Reduction Potential of Consumer Durables
: A Case Study of Air Conditioners in Japan

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by

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Contents

Chapter 1. Introduction

1.1 Issues about climate change

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 (UNFCCC, 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 (UNFCCC, 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 Greenhouse gases (GHG), the cause of global warming, is becoming increasingly urgent, and that measures to combat the problem must now be rapidly worked out.

Figure 1.1 shows the trend of GHG emissions in the world during the period: 1970 to 2010 reported by the International Panel of Climate Change (IPCC) Working group III in 2014 (IPCC, 2014). The total of the GHG emissions in the world have been increasing since 1970. Especially, the annual increase rate of the GHG emissions during the period: 2000 to 2010 was 2.2% and the rate during this decade is higher than that during: 1970 to 2000 (1.3%). This means that we have to consider reducing the GHG emissions more seriously. Looking at the type of the greenhouse gases in 2010, CO_2 accounted for approximately 76% of the total GHG emissions and CO_2 is the main driver of global warming.

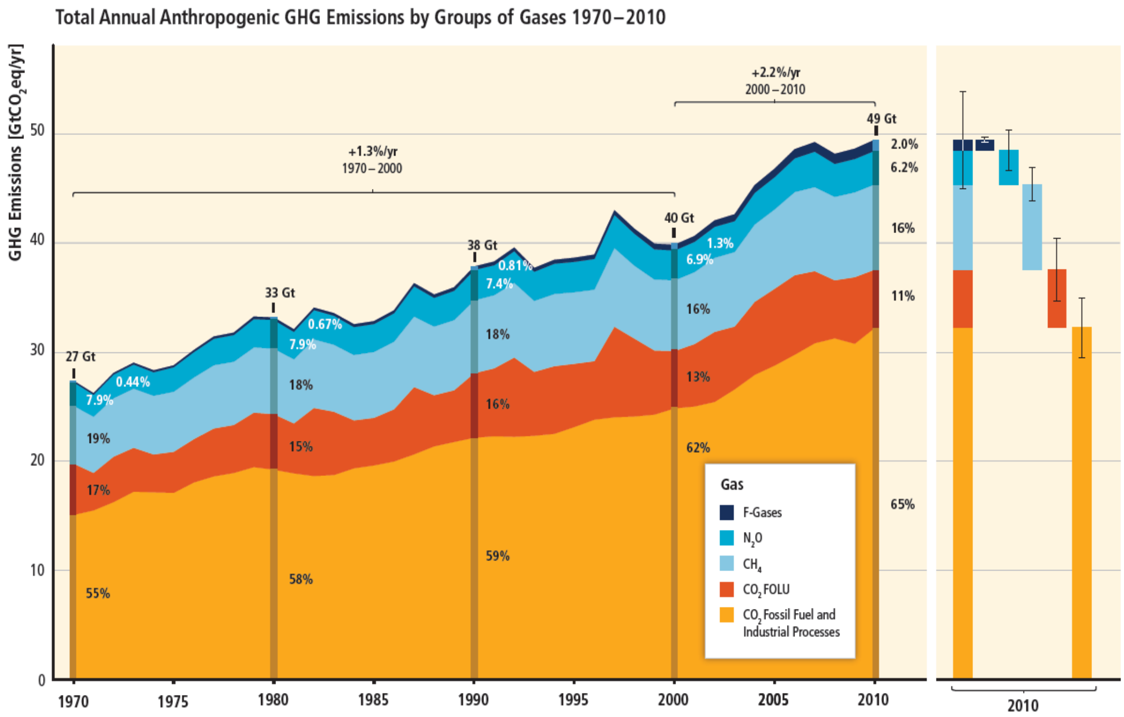

Figure 1.1 Trend and composition of greenhouse gas emissions (GHG) in the world between 1970 and 2010 (IPCC, 2014)

While climate policies can be approached from a wide variety of viewpoints, the lifestyles and behavior patterns of consumers are considered an important factor in terms of impacts on global warming (International Panel on Climate Change Working Group III, 2014). The International Energy Agency (IEA) shows the world CO_2 emissions for each sector in 2014 and reported that residential sector not only directly emitted 6% of the world CO_2 emissions, but indirectly induced 11% of the world CO_2 emissions due to electricity and heat utilizations in 2014 (IEA, 2016). The total CO_2 emissions caused by residential sector accounted for 17% of the world CO_2 emissions and the residential sector is one of the key sector for reducing CO_2 emissions.

Residential sector is also one of the main drivers of CO_2 emissions in Japan. According to the trend of the CO_2 emissions by sector in Japan reported by the Ministry of the Environment of Japan (Ministry of the Environment of Japan, 2016), the residential sector is the fourth largest sector of CO_2 emissions in Japan at 2014. It is important to note that CO_2 emissions from the residential sector entirely tend to increase since 1990, whereas those from the other sectors entirely tend to decrease or be stable during the same period. It indicates that the importance of reducing the CO_2 emissions from residential sector have been increasing.

1.2 Impacts of durable goods on climate mitigation

In particular, since durable goods such as automobiles and home appliances are so essential to our lifestyles, the CO_2 emitted by their manufacture and use makes a large contribution to the global warming, and many previous studies have used a variety of techniques and approaches to quantitatively assess the energy use and the CO_2 emissions attributable to durable goods (Yokota *et al*., 2003; Kim *et al*., 2004; Elshkaki *et al*., 2005; Kagawa *et al*., 2006, 2008, 2009, 2011, 2015; Pout and Hitchin, 2009; Akpinar-Ferrand and Singh, 2010; Steubing *et al*., 2010; Hertwich and Roux, 2011; Olonscheck et al., 2011; Chan *et al*., 2013; Scown *et al*., 2013; Alberini and Bigano, 2015; Taptich *et al*., 2016; Waite *et al*., 2017). Based on electricity use of residential sector in Japan at 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, 2010). Moreover, according to the previous study (Isaac and van Vuuren, 2009), the global CO_2 emissions from air conditioners in residential sector will increase rapidly in the future because of the changes in temperature derived from the climate change. From these viewpoints, it is important to analyze CO_2 emissions from air conditioners for climate mitigation.

1.3 Structure of this dissertation

This Ph.D. dissertation comprises five chapters (See Figure 1.2). Chapter 2 conducts a review of relevant existing previous studies, identifies the contributions of those previous studies, and describes the significance and objectives of this dissertation. Chapter 3 constructs an estimation framework for CO_2 emissions focusing on air conditioners in Japan as a case study, and evaluates the effects of change in product lifetime and energy efficiency (annual electricity consumption) on the CO_2 emissions. Chapter 4 extends the estimation framework constructed in chapter 3 to environmental input-output model, conducts a comprehensive analysis for discussing polices about reducing CO_2 emissions caused by air conditioners in Japan from viewpoints of industrial technology, product lifetime and energy efficiency, and discusses polices for reducing the CO_2 emissions. Finally, Chapter 5 summarizes the results obtained from Chapters 3 and 4, and presents the conclusions of this dissertation.

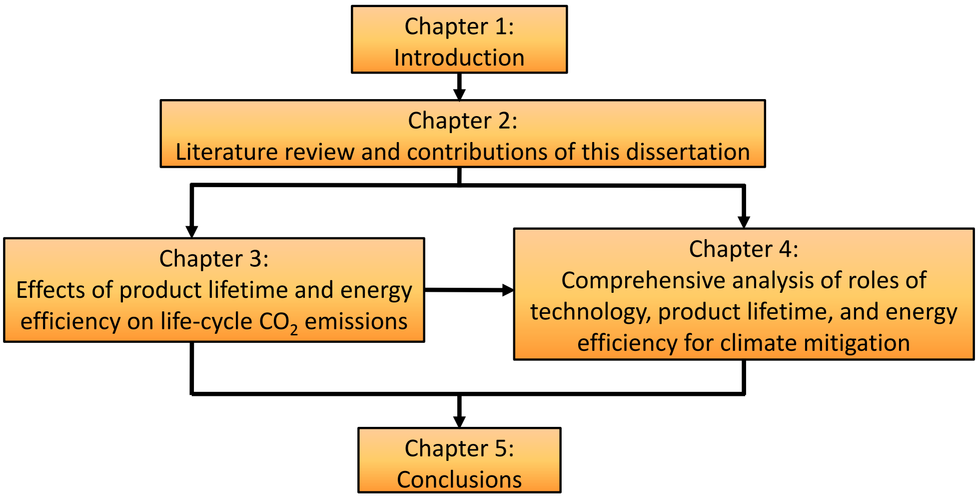

Figure 1.2 Structure of this doctor dissertation

The contents of chapter 3 and chapter 4 in this doctor dissertation are research work published in the following peer-reviewed papers respectively.

Chapter 3:

Nishijima, D., 2016. Product Lifetime, Energy Efficiency and Climate Change: A Case Study of Air Conditioner in Japan. *Journal of Environmental Management*, vol.181, 582–589.

Chapter 4:

Nishijima, D., 2017. The Role of Technology, Product Lifetime, and Energy Efficiency

in Climate Mitigation: A Case study of Air Conditioners in Japan. *Energy Policy*, vol.104, 340–347.

Chapter 2. Literature review and research objectives

2.1 Relationship between product lifetime and life-cycle environmental burdens

How long consumers use their own durable goods is a critical factor for environmental burdens. This is so called "product lifetime." We can consider mainly two directions about product lifetime; shortening product lifetime and extending product lifetime. When the product lifetime of durable goods is shortened, replacement cycle of durable goods becomes faster and energy consumptions at use phase decrease due to improving energy efficiency of the durable goods. It can reduce environmental burdens at use phase, whereas the environmental burdens at disposal and production phases increase by increasing the amount of end-of–life products and new products. On the other hand, when product lifetime of durable goods is extended, replacement cycle of durable goods becomes slower and disposal and production of durable goods decrease. It can reduce environmental burdens at production and disposal phases, whereas it increases environmental burdens at use phase due to using old products with lower energy efficiency. As I mentioned above, there is a trade-off between environmental burdens caused at production and disposal phases and use phase. It is important to evaluate which direction of product lifetime (shortening or extension) is better for the environment. Therefore, studies focusing on the impacts of product lifetime change are main stream of research fields that estimate environmental burdens from durable goods.

Life Cycle Assessment (LCA) gives us helpful information on the above research question. In LCA, an analyst can estimate the entire environmental burdens of a particular good considering not only use phase but resource mining, production, distribution, and disposal phases. The LCA can be applied to ‘vintage’ and ‘new’ durable goods, so we can compare environmental burdens associated with a ‘vintage’ durable product with those associated with a ‘new’ product and decide whether or not we replace our own ‘vintage’ products with ‘new’ ones from an environmental viewpoint.

There are many previous studies using LCA methodology (Ayres, 1995; Spielmann and Altaus, 2007; Eriksson *et al*., 2007; Samaras and Meisterling, 2008; Du *et al*., 2010; Deng *et al*., 2011; Grignon-Massé *et al*., 2011; Aktas and Bilec, 2012; Chester and Horvath, 2012; Basbagill *et al*., 2013; Hawkins *et al*., 2013; Ardente and Mathieux, 2014; Bakker *et al*., 2014; Garcia *et al*., 2015; Suckling and Lee, 2015; Xiao *et al*., 2015; Bobba *et al*. 2016; Iraldo *et al*, 2016; Parikh and Parikh, 2016)

For a seminal study, Kiatkittipong *et al*. (2008) conducted life cycle assessments of computer monitors, refrigerators, light bulbs, and induction motors and showed whether we should purchase new products by comparing accumulated energy consumptions of new products with those of old products as to each product.

Tasaki *et al*. (2012) proposed a visualization of results obtained by the life cycle assessment. Tasaki *et al*. (2012) focused on 3 types of home appliances (TV, air conditioner, and refrigerator) in Japan and they conducted life cycle assessments considering product size, environmental benefits of replacing vintage products with new products, and frequency of product use. They converted the results of the life cycle assessments into diagrams for consumers' decision making about whether replacing with new products is environmentally preferable.

Related to the life cycle assessment, some previous studies proposed calculation methodologies about when and how often replacement of durable goods should be carried out to minimize life cycle environmental burdens in a certain period. This analysis framework is called "Life Cycle Optimization (LCO)" (Kim *et al*., 2003, 2006; Spitzley *et al*., 2005; Bole, 2006; De Kleine *et al*., 2011). The LCO finds a best replacement schedule of a particular durable good to minimize the life cycle environmental burdens by dynamic programming. For example, Kim *et al*. (2003) applied the LCO methodology to automobile replacement and provided the best replacement schedule for minimizing CO, CO_2 NMHC, and NO_x respectively. There are also some previous studies that proposed calculation methodologies of replacement schedules to minimize environmental burdens other than LCO methodology (Chalkley *et al*, 2003; Mijailović, 2013; Skelton and Allwood, 2013; Mizuno *et al*., 2015; Eryilmaz, 2017).

The life cycle assessment can consider the environmental burdens caused by both shortening and extending product lifetime of durable goods. There are previous studies that analyzed impacts of shortening and extending product lifetime respectively on environmental burdens from durable goods. Some previous studies analyzed the impact of a scrappage scheme on environmental burdens from durable goods. (Baltas and Xepapadeas, 1999; ECMT, 1999; Van Wee *et al*., 2000, 2011; Dill 2004; BenDor and

Ford, 2006; Lelli *et al*., 2010; Lenski *et al*., 2010; Brand *et al*., 2011; Sandler, 2012; Li *et al*., 2013; Antweiler and Gulati, 2015; DeShazo *et al*., 2017). A scrappage scheme are is a policy in which a government gives consumers incentives for replacing new high energy-efficient products that a government targets. Scrappage schemes have been widely introduced in many countries not only for environmental policy but also for a measure for stimulating economy.

Lavee and Becker (2009) analyzed the impact of an accelerated vehicle retirement program in Israel by cost-benefit analysis. They considered three types of cars that are private cars, trucks and buses. They found that for private cars, an accelerated vehicle scrappage program can generate significant benefits and lower air pollution by approximately 17%. Conversely, conducting an accelerated vehicle scrappage program for buses and trucks makes negative net benefits. They also discussed the causes of the difference in effect of the program to private cars and trucks and buses. They mentioned that differences in natural retirement rate or reduction rate of air pollution due to replacement between car types make the difference in effects of the program.

Lenski *et al*. (2013) conducted a cost-benefit analysis of the vehicle scrappage program in US which is also called ‘Cash for Clunkers’ considering both economic and environmental benefits at a life cycle perspective. They showed that the vehicle scrappage program could contribute to avoiding carbon dioxide and pollutant emissions. They also discussed more effective design of the vehicle scrappage program. They pointed out that more economic and environmental benefits could have been achieved by a lower value of rebate, auction mechanism for setting rebate value, and targeting to areas where damages from emissions are relatively higher.

There are also some previous studies focusing on effects of product lifetime extension on environmental burdens from durable goods (Cooper, 2005; Kagawa *et al*., 2008, 2009, 2011; Defra, 2011). For example, Kagawa *et al*. (2006) quantitatively analyzed impacts of product lifetime extension of automobiles on energy consumptions and economy in Japan by the environmental input-output framework considering some consumption pattern shifts induced by product lifetime extension. They revealed that product lifetime extension can realize significant energy consumptions and GDP increase if consumers spend income gains obtained from product lifetime extension on consumer services.

2.2 Scenario analyses for future environmental burdens associated with stock and flow of durable goods

There is another main research field about environmental burdens from durable goods. That is a scenario analysis about future environmental burdens from durable goods focusing on stock and flow of durable goods. This research field can give an estimation framework for the environmental burdens including some factors (e.g. population, distribution rate, product lifetime, energy efficiency in use) as parameters. Once we construct the forecasting framework, we can estimate the future environmental burdens from consumer durables using the framework. Changing the parameters in the framework and comparing the estimation results, we can also evaluate the reduction potential of changes in each factor and propose combined scenarios for achieving a reduction target of environmental burdens. As to environmental burdens from durable goods, we firstly set initial number of stock of particular durable goods and estimate the future number of stock, replacement demand, and waste of durable goods. Then, we forecast the environmental burdens from durable goods by multiplying those estimated numbers by emission coefficients (Lumbreras *et al*., 2008; Yang, *et al*., 2009; Kromer *et al*., 2010; Hao *et al*., 2011, 2016; Baptista *et al*., 2012; Palencia *et al*., 2012; Singh and

Strømman, 2013; Ürge-Vorsatz *et al*. 2015; Mittal *et al*., 2016; Alam *et al*., 2017; Zhao and Heywood, 2017).

Müller (2006) introduced a material flow analysis system for stock dynamics considering population, product lifetime, material intensity and service unit a stock provides. He applied the analysis into concrete in housing stock in Netherland as a case study and estimated the future stock of concrete in housing. Moreover, he changed the values of parameters about product lifetime, material intensity and useful floor area (service unit of housing in this study) and analyzed the effects of those changes on concrete stock in housing.

Melaina and Webster (2011) developed a formula for estimating greenhouse gas emissions from motor vehicle travel, utilizing three factors that are travel distance per a unit, fuel consumption, and fuel carbon intensity. They also conducted scenario analyses aimed at achieving the greenhouse gas emission target set by the U.S. government for the year 2050. They showed that all the three factors must progress significantly for achieving the greenhouse gas reduction target.

2.3 Statistical estimation of product lifetime models

Most of the previous studies about environmental burdens from durable goods used statistical product lifetime models. The widely-used statistical product lifetime model is lifetime distribution (or lifetime function). This product lifetime model expresses a relationship between disposal rate (survival rate) of a particular durable good and their usage duration. Using this product lifetime distribution, we can get the disposal or survival probabilities of durable goods corresponding to their usage duration and also can calculate the stock of materials and products (Bergsdal *et al*., 2007; Oguchi *et al*., 2008; Hu *et al*., 2010; Huo and Wang, 2012; Pauliuk and Müller, 2014; Chen and Graedel, 2015; Golev *et al*., 2016; Cao *et al*., 2017;Guo and Yan, 2017; Miatto *et al*., 2017), the number of waste products (Kim *et al*., 2008; Walk, 2009; Oguchi *et al*., 2010; Zhang *et al*., 2011; Araújo *et al*., 2012; Polák and Drápalová, 2012; Pant 2013; Hauber *et al*., 2014; Rahmani *et al*., 2014), material or substance flow (Melo, 1999; Kleijn *et al*., 2000; Tasaki et al., 2004; Davis *et al*., 2007; Hashimoto *et al*., 2007; Yoshida *et al*., 2009; Kapur *et al*., 2008; Hatayama *et al*., 2010; Huang *et al*., 2013; Lam *et al*., 2013; Pauliuk *et al*., 2017), and associated environmental burdens (Samaras *et al*., 1999; van der Voet *et al*., 2002; Kakudate *et al*., 2002; Cheah *et al*., 2009; Yan and Crookes 2009;

Zhou *et al*., 2011; Cai *et al*., 2015; Xue *et al*., 2017). The product lifetime distribution has such benefits for estimating environmental burdens induced by durable goods and it has been widely used in many previous studies.

The product lifetime distributions are statistically estimated by actual data about existing or disposed products based on some types of distribution function. As to product lifetime function of durable goods, Weibull distribution function has been widely used and statistically well fitted for estimating the product lifetime. Murakami *et al*. (2010) and Oguchi *et al*. (2010) explained about definitions of some types of product lifetime, estimation methodologies of product lifetime distribution, and information on data of product lifetime distribution more concretely. Many product lifetime distributions have been estimated as to a variety of products in different countries (Bayus, 1988; Cohen and Whitten, 1988; Islam and Meade, 2000; Tasaki *et al*., 2001; Oguchi *et al*., 2006, 2010; Erumban, 2008; Babbitt *et al*., 2009; Murakami *et al*., 2010; Kagawa *et al*., 2011; Daigo *et al*., 2007, 2015; Oguchi and Fuse, 2015, Miller *et al*., 2016); Petridis *et al*., 2016; Weymar and Finkbeiner, 2016).

2.4 Contributions of this dissertation

From the comprehensive overview of the previous studies about environmental burdens from durable goods, those previous studies contributed to discussions about reducing environmental burdens from durable goods mainly on the following two points.

The first point is that the previous studies have clarified the relationship between product lifetime and environmental burdens induced by durable goods. As I mentioned in section 2.1, product lifetime has a large influence on those environmental burdens. In that point, life cycle assessment considers both shortening and extending product lifetime as measures for reducing the environmental burdens. There are also previous studies focused on the effects of shortening or extending product lifetime respectively on environmental burdens from durable goods. Those previous studies help us to discuss how long we should use our own products from an environmental perspective.

The second point is that the previous studies have shown the reduction potential of not only product lifetime change but the other factors such as change in energy efficiency and/or technologies of durable goods. Previous studies in section 2.2 constructed estimation frameworks of environmental burdens based on stock of durable goods including a variety of factors such as population and carbon or material intensity. These previous studies not only estimated environmental burdens derived from durable goods in the future, but also showed integrated scenarios for achieving particular reduction targets. The results can help especially policymakers to understand how they can achieve reduction targets they are imposed.

However, the previous studies have not analyzed yet as below. One is that they have not statistically modeled empirical trends of energy efficiency in use of durable goods. When we discuss the reduction potential of energy efficiency improvement for reducing environmental burdens, we should consider historical technological progress about energy efficiency. Although some previous studies analyzed effects of energy efficiency improvement on environmental burdens induced by durable goods, they did not consider that point. We should capture features of historical trend of energy efficiency by statistically modelling empirical trend of energy efficiency and discuss reduction policies of the environmental burdens more empirically.

The other point is that the previous studies did not discuss reduction of environmental burdens from durable goods with simultaneous consideration of both micro factors such as product lifetime and energy efficiency of particular durable goods, and macro factors such as industrial technologies surrounding the durable goods including supply chains. Most of the previous studies focused on reduction measures of environmental burdens from durable goods based on product lifetime or energy efficiency. However, upstream industries centered around durable goods have also an important role of reducing life-cycle environmental burdens from the durable goods and we should take those industries into account for discussing reductions in the environmental burdens along the supply-chains. Few previous studies considered the impacts of industries surrounding durable goods on the environmental burdens and there is no comprehensive analysis for the environmental burdens simultaneously considering product lifetime, energy efficiency, and industries related to durable goods.

Motivated by the shortcomings of the previous studies above, this doctoral dissertation focuses on life-cycle CO_2 emissions caused by air conditioners in Japan as a case study. In chapter 3, I statistically model the product lifetime and trend of energy efficiency of air conditioners in Japan. Using those models, I estimate the number of stock and replacement of air conditioners and CO_2 emissions induced by air conditioners. Finally, I conduct scenario analyses about the effects of change in product lifetime and energy efficiency in use of air conditioners on CO_2 emissions. Through the results, I evaluate the CO_2 reduction potential of change in product lifetime and energy efficiency and quantitatively show a target value of improvement rate of energy efficiency for conducting scrappage schemes such as "Home appliance eco-point program". In chapter 4, I connect the models of product lifetime and energy efficiency modeled in chapter 3 with the environmental input-output framework and construct the comprehensive analytical framework for CO_2 emissions induced by air conditioners in Japan during the period from 1990 to 2005. Using the constructed framework, I conduct a structural decomposition analysis to find specific industrial sectors that indirectly contributed to increasing the CO_2 emissions during the period. I also conduct scenario analyses about the impacts of change in product lifetime and energy efficiency on the CO_2 emissions and quantitatively shows combinations of shortening or extending product lifetime and energy efficiency improvement necessary for holding the CO_2 emissions in 2005 at 1990 level. Finally, based on the results of analyses above, I discuss comprehensively how we should reduce CO_2 emissions induced by air conditioners from viewpoints of industrial technology surrounding air conditioners, product lifetime, and energy efficiency.

This doctoral dissertation discusses reduction measures of CO_2 emissions induced by air conditioners in Japan comprehensively considering not only microscopic factors of durable goods such as product lifetime and energy efficiency in use, but macroscopic factors such as technology of industries surrounding the durable goods. The outcomes showed in this dissertation are useful for policymakers and durable goods industries and also enable us to develop discussions for reducing CO_2 emissions from durable goods.

Chapter 3 Effects of product lifetime and energy efficiency on life-cycle CO_2 emissions

3.1 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. As a result of the various initiatives, Japan took toward climate mitigation, it managed to reduce GHG emissions in 2014 by 3.1% compared to those in 2013 (Ministry of the Environment of Japan, 2016). However, since Japan has to conduct a reduction of 26% GHG emissions by 2030 compared to 2013 in Paris Agreement (Ministry of Foreign Affair of Japan, 2016), additional GHG reductions are needed. The residential sector accounted for a substantial proportion of total emissions—15.2% in 2014 (Ministry of the Environment of Japan, 2016)—so the reduction of total residential CO_2 emissions appears to be an urgent challenge for Japan.

As I described in chapter 1, 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, 2010). 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 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.

Many previous studies focused on the trade-off above mentioned and estimated the impacts of product lifetime and energy efficiency of durable goods on environmental burdens (Kondo and Nakamura, 2004; Van Schaik and Reuter, 2004; Müller *et al*., 2006; Nakamura and Kondo, 2006; Ou *et al*., 2010; Beccali *et al*., 2013, 2014, 2016; Cellura *et al*., 2014; Finocchiaro *et al*., 2016). Kagawa *et al*. (2011) evaluated the impacts of change in product lifetime on total CO_2 emissions from vehicle use in Japan and showed that extending product lifetime of vehicles can contribute to reducing CO_2 emissions. 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 modeled 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. Finally, they did not show 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 chapter, 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 modeled 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 in order to investigate how changes in product lifetime and energy efficiency impact the lifecycle CO_2 emissions and how much we should improve energy efficiency of air conditioners for holding back the reduction of CO_2 emissions that occurs when the lifetime of air conditioners becomes shorter (by accelerating new replacement purchases). 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 3.2 provides a literature review; Section 3.2 formulates the methodology developed in this study; Section 3.3 presents the empirical results and discussion; Section 3.4 presents our conclusions.

3.2 Methodology

3.2.1 Estimating the stock of residential air conditioners and the number of new residential air conditioners sold each year

The survival rate in year t of the air conditioners newly sold in year i, φ_{t-i} is assumed to follow a Weibull distribution, as follows:

$$\varphi_{t-i} = \exp\left\{-\left(\frac{t-i}{\alpha}\right)^{\beta}\right\} \qquad (t \geq i) \tag{3.1}$$

where α and β respectively represent the scale parameter and shape parameter of the distribution. Weibull distributions fit the data well and are widely used to model the product lifetimes of various kinds of durable goods (e.g., Kagawa *et al*., 2011; Oguchi and Fuse, 2015). Note that when $t = i$, Eq. (3.1) gives the proportion of the new household air conditioners sold in year i that remain in use in year i as 1. The mean value of the Weibull distribution function (that is, average product lifetime) μ is given by

$$\mu = \alpha\Gamma\left(1+\frac{1}{\beta}\right) \tag{3.2}$$

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 set the values of scale parameter α and shape parameter β to 7.9 and 1.8 respectively, as specified in the research report "Reuse Promotion of End-of-Life Products" (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 $\overline{\mu}=12.6$ years.

Specifying the survival rate of air conditioners as in Eq. (3.1), the stock of residential air conditioners $S_t(\overline{\mu})$ in year t can be estimated using the following equation:

$$S_t(\overline{\mu}) = B_t(\overline{\mu}) + \sum_{i=1}^{t-1}\varphi_{t-i}(\overline{\mu})B_i(\overline{\mu}) \tag{3.3}$$

where $B_t(\overline{\mu})$ $(B_i(\overline{\mu}))$ and $\varphi_{t-i}(\overline{\mu})$ are the number of newly sold residential air conditioners in year t (i), and the survival rate in condition that average lifetime of air conditioners is $\overline{\mu}=12.6$ years, respectively..

Using the data on annual new shipments of residential air conditioners in Japan for the 42 years from 1972 to 2013, as published by the Japan Air Refrigeration and Air Conditioning Industry Association (The Japan Air Refrigeration and Air Conditioning Industry Association, 2015) (see Table 3A of the Appendix 3A for the shipment data) as $B_i(\bar{\mu})\,(i = 1972, 1973, \cdots, 2013)$ in Eq. (3.3), which expands to the system of equations

$$\begin{cases} S_{1972}(\bar{\mu}) = B_{1972}(\bar{\mu}) \\ S_{1973}(\bar{\mu}) = B_{1973}(\bar{\mu}) + \varphi_1(\bar{\mu})B_{1972}(\bar{\mu}) \\ S_{1974}(\bar{\mu}) = B_{1974}(\bar{\mu}) + \varphi_1(\bar{\mu})B_{1973}(\bar{\mu}) + \varphi_2(\bar{\mu})B_{1972}(\bar{\mu}) \\ \vdots \\ S_{2013}(\bar{\mu}) = B_{2013}(\bar{\mu}) + \varphi_1(\bar{\mu})B_{2012}(\bar{\mu}) + \varphi_2(\bar{\mu})B_{2011}(\bar{\mu}) + \cdots + \varphi_{41}(\bar{\mu})B_{1972}(\bar{\mu}) \end{cases} \tag{3.4}$$

I estimated the stock of air conditioners in each year on the basis of the current average product lifetime. Note that I assume that all air conditioners are following the same lifetime distribution, irrespective of their age (i.e., year of production).

For purposes of analysis, in this study the stock of air conditioners in each year estimated using Eq. (3.4), remains constant with respect to lifetime. Under this assumption, I consider a change in the average product lifetime of air conditioners from $\bar{\mu} = 12.6$ to $\mu*$ such that the survival rate changes from $\varphi_{t-i}(\bar{\mu})$ to $\varphi_{t-i}(\mu*)$ while remaining a Weibull distribution. Then from eq. (3.4), the annual numbers of new residential air conditioners sold in the 42-year period from 1972 to 2013 $B_i(\mu^*)\,(i = 1972, 1973, \cdots, 2013)$ can be estimated sequentially as follows:

$$\begin{cases} B_{1972}(\mu^*) = S_{1972}(\mu^*) = S_{1972}(\bar{\mu}) \\ B_{1973}(\mu^*) = S_{1973}(\mu^*) - \varphi_1(\mu^*) B_{1972}(\mu^*) \\ B_{1974}(\mu^*) = S_{1974}(\mu^*) - \varphi_1(\mu^*) B_{1973}(\mu^*) - \varphi_2(\mu^*) B_{1972}(\mu^*) \\ \vdots \\ B_{2013}(\mu^*) = S_{2013}(\mu^*) - \varphi_1(\mu^*) B_{2012}(\mu:) - \varphi_2(\mu^*) B_{2011}(\mu^*) - \cdots - \varphi_{41}(\mu^*) B_{1972}(\mu^*) \end{cases} \tag{3.5}$$

3.2.2 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,

$$\lambda_i = K\{1 + \exp(a - bi))\} \tag{3.6}$$

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.

I 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, 2010, 2011, 2012, 2013, 2014) to estimate the reverse logistic function. The data used in this estimation are provided in Table 3B of Appendix 3B. I estimated the function parameters $\hat{a}$ and $\hat{b}$ in eq. (3.6) for different fixed critical values K and obtained the coefficient of determination of the reverse logistic curve by regression analyses. I obtained the highest coefficient of determination $(R^2 = 0.966)$ with values $\hat{K} = 824$, $\hat{a} = -0.166$, and $\hat{b} = 0.197$ (see Fig. 3.1).

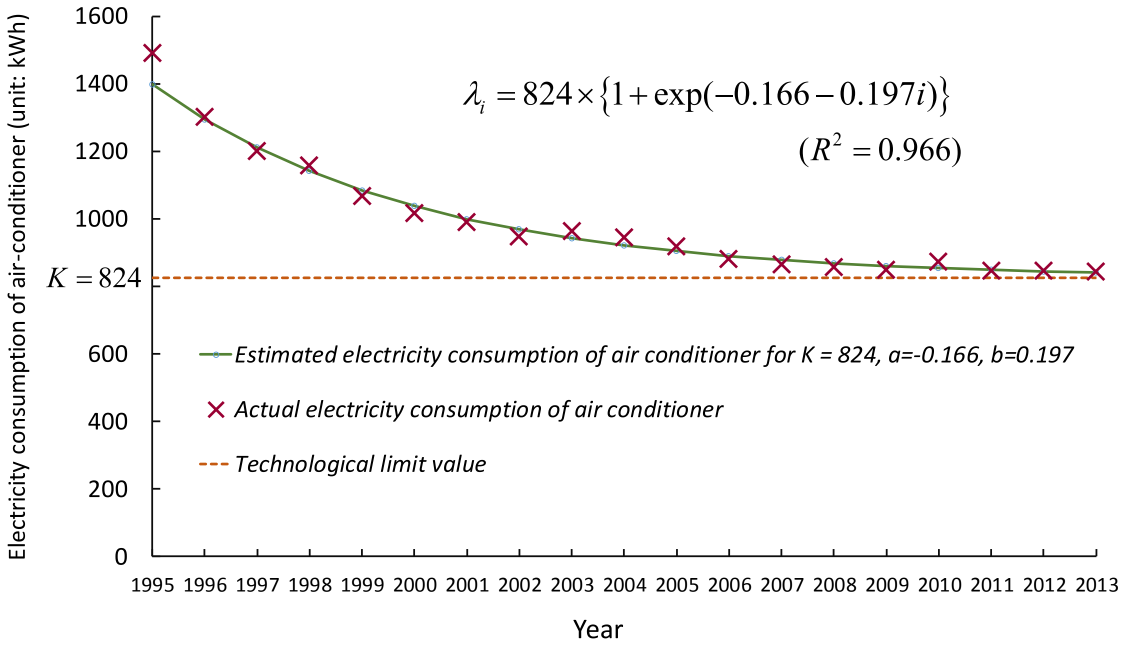

Figure 3.1 Catalog-based annual electricity consumption of an "average" residential air conditioner and estimated consumption based on a reverse logistic function

In the following analysis, I assume the annual electricity consumption of residential air conditioners manufactured in each year on a baseline to follow Eq. (3.6) for $K = 824$. Because I could not obtain electricity consumption data for household air conditioners for 1994 or earlier years, I assumed for this study that air conditioner electricity consumption for the years up to 1994 was the same as that for air conditioners manufactured in 1995.

The estimated value $\hat{K}$ can be considered a critical electricity consumption value expressing a technological limit for household air conditioners, which can be estimated from empirical values of electricity consumption. That is, the electricity consumption of household air conditioners is changing from 1,492 kWh in 1995 to a future technological limit value of 824 kWh.

It is well known that the annual electricity consumption of an "average" residential air conditioner provided by the "Energy-saving Performance Catalog" database (i.e. catalog-based annual electricity consumption) is not the 'actual' annual electricity consumption occurring in the residential sector. According to the research report by the National Institute of Advanced Industrial Science and Technology (AIST) of Japan (2010), the actual annual electricity consumption of residential air conditioners is 18% of the catalog-based annual electricity consumption if one considers usage time of residential air conditioners. Thus, in this study, I multiply the values of λ_i by 18% and use the results as the annual electricity consumption of air conditioners produced for the corresponding years.

3.2.3 Method of estimating the electricity consumption and CO_2 emissions of residential air conditioners

Next, I estimate the total electricity consumption of air conditioners during their use phase. The electricity consumed in year *t* by residential air conditioners $C(t)$ can be expressed as follows:

$$C(t) = \sum_{i=1972}^{t} \lambda_i \varphi_{t-i}(\mu^*) B_i(\mu^*) \tag{3.7}$$

Then, by multiplying Eq. (3.7) by the life-cycle CO_2 emissions coefficient per kilowatt-hour for air conditioners in the use phase δ_r, the CO_2 emissions from air conditioners in year t, $E_r(t)$, is calculated as follows:

$$E_r(t) = \delta_r C(t) \tag{3.8}$$

Next, I estimate $E_p(t)$, the CO_2 emissions of residential air conditioners in the production phase in year t. This is done using the life-cycle CO_2 emissions coefficient

δ_p, which represents the quantity of emissions generated in manufacturing one air conditioner, as follows:

$$E_p(t) = \delta_p B_t(\mu^*) \tag{3.9}$$

The life-cycle CO_2 emissions coefficients for the use and production phases were set as $\delta_r = 0.0005$ $\delta_r = 0.0005$ and $\delta_p = 0.31$ (tonnes of CO_2 equivalent), respectively, based on "Guidelines for the Calculation of Greenhouse Gas Emission Intensities Throughout the Supply Chain Ver. 2.1" (Ministry of the Environment of Japan, 2014). In this study, it is assumed that air conditioners purchased in year t are manufactured in that same year.

Now, using Eqs. (3.8) and (3.9), the total life-cycle CO_2 emissions $E(t)$ for residential air conditioners can be determined as follows.

$$E(t) = E_r(t) + E_p(t) \tag{3.10}$$

3.2.4 Scenario analysis of the influence on CO_2 emissions of changes in average lifetime and the critical value of electricity consumption of residential air conditioners

I will explain the scenario analyses on how the average product lifetime of residential air conditioners influences total CO_2 emissions. I vary the average product lifetime by changing the mean value μ of the Weibull distribution function shown in Eq. (3.1) and analyze the impacts of these changes on total CO_2 emissions. I estimate life-cycle CO_2 emissions when the average lifetime is reduced by 1 year and extended by 1 year relative to the average lifetime value of 12.6 years estimated by the Ministry of the Environment (2011). More specifically, along the lines of Kagawa *et al*. (2006, 2009, 2011), I fix the value of the shape parameter β at 1.8 and re-estimate the values of α required to make the average lifetime in Eq. (3.2) 11.6 and 13.6 for the shorter and longer lifetime scenarios, respectively. Then from the Weibull distribution functions obtained with both parameters, I determine the survival rate for each scenario and estimate the life-cycle CO_2 emissions for both the use and production phases from Eqs. (3.8) and (3.9).

Next, I conduct a scenario analysis to assess how changes in the critical value of annual electricity consumption of residential air conditioners K influences life-cycle CO_2 emissions. More specifically, I estimate the electricity consumption in the case that the critical value of annual electricity consumption is reduced by $\varepsilon \times 100\%$ from $\hat{K} = 824$, i.e., to $(1-\varepsilon)\hat{K}$. It is noted that when $\varepsilon = 0$, the values of Eq. (3.6) are annual electricity consumption of air conditioners manufactured in each year as a baseline In this study, I set the value of the parameters in Eq. (3.6) to $\hat{a} = -0.166$ and $\hat{b} = 0.197$ to determine the annual electricity consumption λ_i of residential air conditioners manufactured in each year for three scenarios: reductions of the electricity consumption limit value by 5% ($\varepsilon = 0.05$), by 10% ($\varepsilon = 0.1$), and by 15% ($\varepsilon = 0.15$). For each of these scenarios, I then estimate the life-cycle CO_2 emissions. This analysis examines the potential for reducing CO_2 emissions not only by changing the average product lifetime but also by improving the energy performance of air conditioners.

3.3 Empirical results and discussion

3.3.1 Trend in stock of residential air conditioners over the years

Figure 3.2 shows the stock of residential air conditioners between 1990 and 2013, as estimated using Eq. (3.4), as well as the number of residential air conditioners that were shipped domestically, according to data provided by the Japan Air Refrigeration and Air Conditioning Industry Association (2015). It is clear from Fig. 3.2 that the total stock of residential air conditioners has consistently risen. Interestingly, despite the fact that Japan's population began to decline between 2009 and 2013 (Statistics Bureau, Japan, 2015), the stock of air conditioners over this period continued to increase in the same manner as below. However, from 1990 to 2013 the number of households in Japan rose steadily from 41.15 to 54.59 million (Statistics Bureau, Japan, 2015), much like the air conditioner numbers. Considering that air conditioners are a type of durable good that is installed on a per-household or per-room basis, it is natural that the stock of air conditioners increase roughly in line with the number of households. From this observation, I find that the air conditioner stock moves primarily in response to the number of households rather than to the current population. According to estimates by the National Institute of Population and Social Security Research of Japan (2013), the number of households in Japan is expected to continue increasing until 2019. In light of this, the stock of air conditioners is also likely to continue rising, which means that the impact of air conditioners on climate change will also continue to grow bigger.

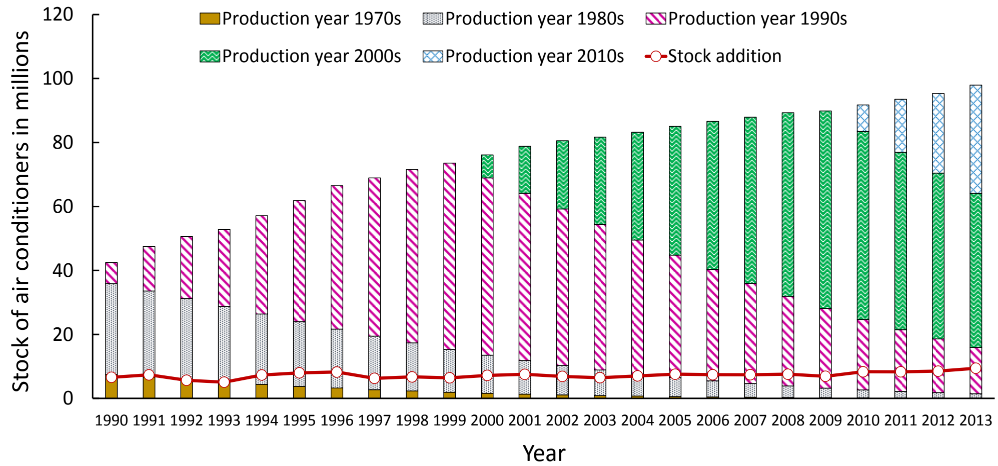

Figure 3.2 Total stock of residential air conditioners and new air conditioner shipments

3.3.2 Change in CO_2 emissions in production and use phases for each average lifetime scenario

Next, I look at life-cycle CO_2 emissions when the average product lifetime is reduced and extended by 1 year from the baseline scenario ($\mu = 12.6, \varepsilon = 0$), to 11.6 and 13.6 years, respectively.

Figure 3.3 shows the change in production-phase CO_2 emissions of residential air conditioners for the baseline level of 12.6 years and extended and reduced by 1 year.

Production-phase CO_2 emissions are lowest for the scenario in which the average product lifetime is extended by 1 year to 13.6 years. This can be explained by the fact that increasing the air conditioner lifetime tends to depress the number of new air conditioners produced. The estimated production-phase CO_2 emissions (in millions of tonnes) in 2013 for the three average product lifetime scenarios are 3.08 for 11.6 years, 2.89 for 12.6 years, and 2.73 for 13.6 years. Thus, extending the average product lifetime by 1 year enables a 5.5% reduction in emissions in 2013 relative to the baseline average product lifetime scenario of 12.6 years.

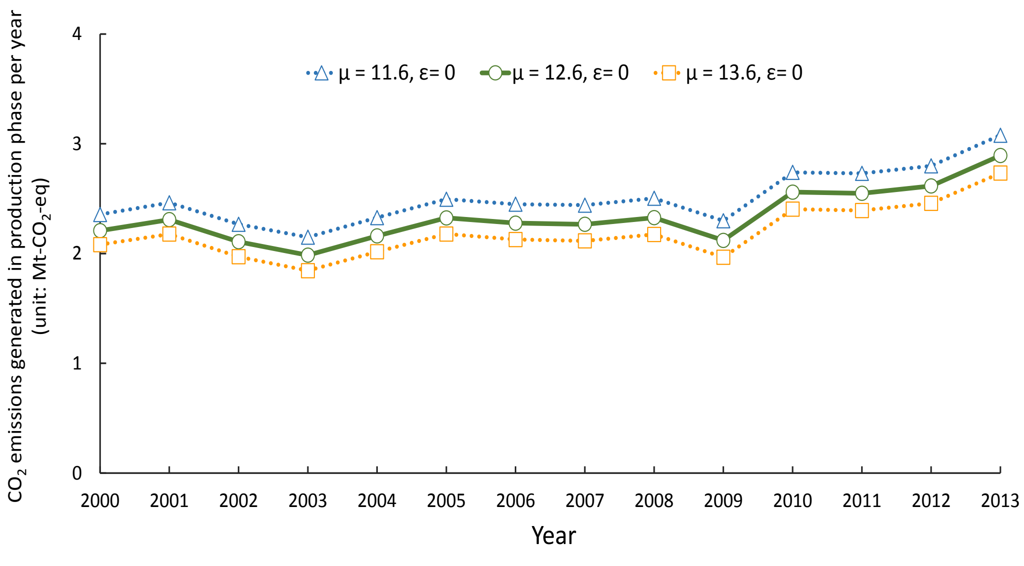

Figure 3.3 Production-phase CO_2 emissions of residential air conditioners for each average product lifetime scenario

Although there was very little difference in use-phase emissions between the scenarios, as shown in Fig. 3.4, emissions are lowest when the average product lifetime is 11.6 years. This is likely to be because a shorter lifetime tends to increase the number of more energy-efficient, newer air conditioners as a proportion of the total stock of air conditioners in use. The use-phase CO_2 emissions (in millions of tonnes) for the three average product lifetimes are 7.72 for 11.6 years, 7.84 for 12.6 years, and 7.96 for 13.6 years. Thus, reducing the average lifetime by 1 year enables a 1.5% reduction in use-phase CO_2 emissions in 2013 relative to the baseline average product lifetime scenario of 12.6 years.

The results reveal 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.

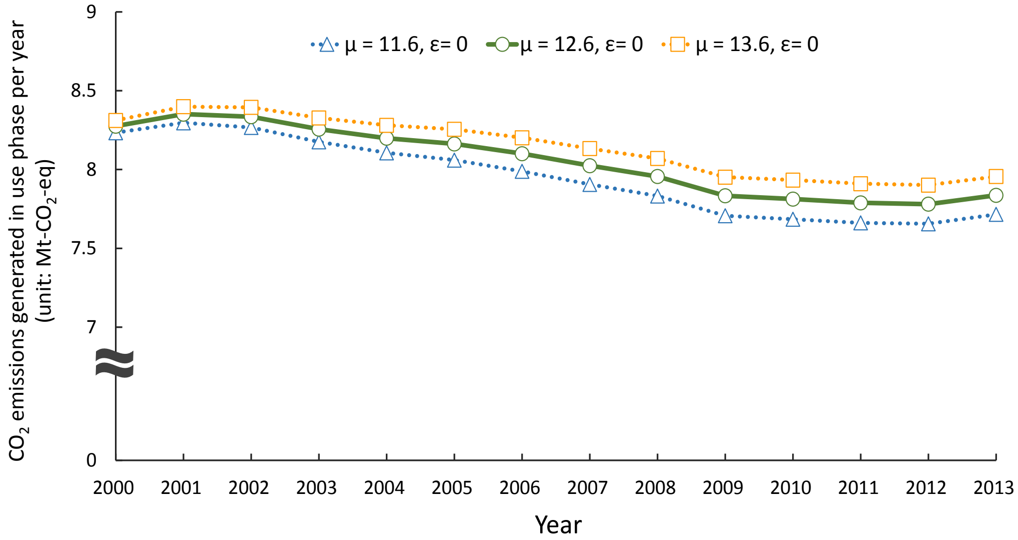

Figure 3.4 Use-phase CO_2 emissions of residential air conditioners for each average product lifetime scenario

3.3.3 Total residential air conditioner CO_2 emissions in production and use phases for each scenario

Here, I show how the total CO_2 emissions for residential air conditioners, from both the production and use phases, are influenced by reducing the average product lifetime by 1 year ($\mu = 11.6, \varepsilon = 0$) and by extending it by 1 year ($\mu = 13.6, \varepsilon = 0$) relative to the baseline value of 12.6 years. It is important to note that further development toward cleaner air conditioners has a large potential for reducing life-cycle CO_2 emissions. Therefore, for the baseline value of the average product lifetime (12.6 years), I also show the effect of lowering the critical value of electricity consumption $\hat{K}=824$ by 5% ($\mu=12.6, \varepsilon=0.05$), 10% ($\mu=12.6, \varepsilon=0.1$), and 15% ($\mu=12.6, \varepsilon=0.15$). Figure 3.5 graphically displays the difference in total CO_2 emissions (production phase plus use phase) for each of these scenarios relative to the baseline case ($\mu=12.6, \varepsilon=0$).

First, the results for total CO_2 emissions for each average product lifetime scenario are that total emissions are lowest when the average product lifetime is extended by 1 year to 13.6 years, and highest when the average product lifetime is reduced by 1 year to 11.6 years. The estimates of total CO_2 emissions (millions of tonnes) for 2013 are 10.79 for 11.6 years, 10.73 for 12.6 years, and 10.69 for 13.6 years. Thus, extending the average product lifetime by 1 year enables a CO_2 emissions reduction of approximately 0.4% in 2013 relative to the baseline scenario. This result suggests that at the current level of air conditioner energy efficiency (technology level) (i.e., $K=824$), reducing life-cycle CO_2 emissions would be more effectively achieved by extending the average product lifetime to make better use of existing air conditioners than by increasing the average energy efficiency of the stock of air conditioners by reducing the average product lifetime.

Next, analysis on how changes in the critical value of electricity consumption influence CO_2 emissions reveals that reducing the critical value of annual electricity consumption by 5%, 10%, and 15% would cut life-cycle CO_2 emissions to 10.34, 9.95, and 9.55 million tonnes, respectively. Also, a comparison of CO_2 emission levels in the case of extending average product lifetime by 1 year to 13.6 years and in the cases of reducing the critical value (of annual electricity consumption) by 5%, 10%, and 15% reveals that emissions can be reduced more by lowering the critical value of annual electricity consumption by 5% than by extending the average product lifetime by 1 year, as shown by Fig. 3.5. An additional finding is that the emission reduction effect of extending the average product lifetime by 3 years is still lower than that of improving the critical value of electricity consumption by 5% (see Fig. 3A at Appendix 3C for more comprehensive results on potential changes in life-cycle CO_2 emissions through changing average product lifetime and the critical value of electricity consumption). This result suggests that if we had to decide whether to try to reduce the life-cycle CO_2 emissions of air conditioners either by extending the average product lifetime or by improving the energy efficiency, it would be better to try to improve the electricity consumption, even taking into account the adverse economic impact due to the depressing effect that extending the average product lifetime has on replacement air conditioner purchases.

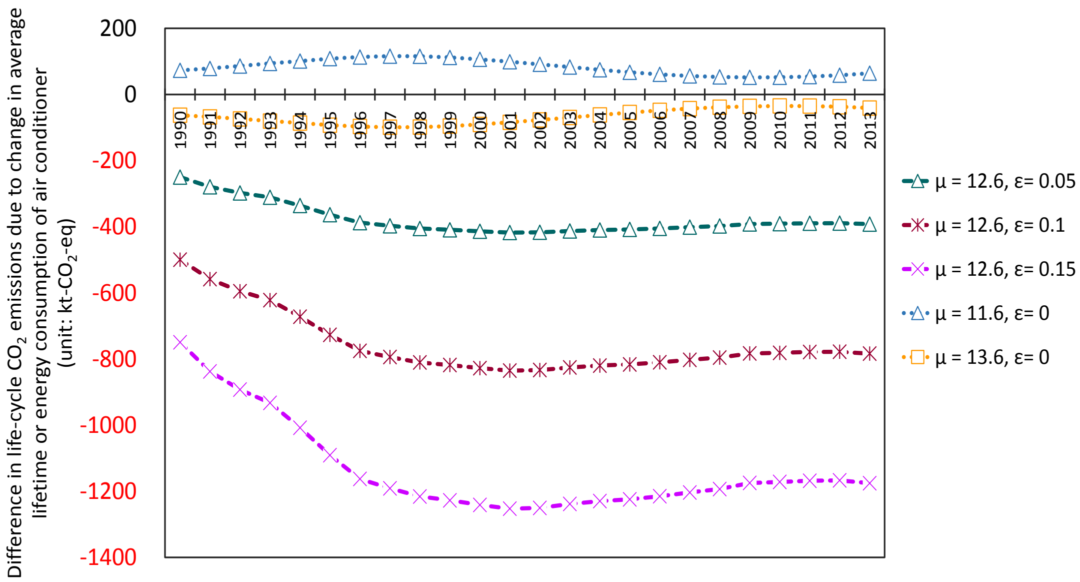

Figure 3.5 Difference in life-cycle CO_2 emissions relative to baseline scenario, for each change scenario

These results indicate that further reducing the electricity consumption of air conditioners is essential for continuing to cut the total CO_2 emissions resulting from residential air conditioners. It is important to give the air conditioning industry an incentive to develop cleaner products through a market expansion policy of highly energy-efficient products, similar to the vehicle scrappage schemes introduced in various countries (European Automobile Manufacturers Association, 2012; Japan Automobile Manufacturers Association, 2012; Executive Office of the President of the

United States, 2009; Institute for Energy and Environmental Research Heidelberg, 2009; The World Bank, 2012). Such measures serve not only to reduce the lifetimes of products but also to improve their energy efficiency.

One important question is how much the energy efficiency of new air conditioners needs to be improved in order to offset the increase in production-phase emissions that occurs due to the additional new air conditioners resulting from a shorter average product lifetime. Figure 3.6 shows life-cycle CO_2 emissions in 2013 when the average product lifetime is simply extended by 1 year to 13.6 years and emissions under scenarios in which the average product lifetime is reduced by 1 year to 11.6 years and, simultaneously, the critical value of annual electricity consumption is reduced by 1.4%, 5%, 10%, and 15% relative to its current level, i.e., $K = 824$.

These result show that even at the reduced average product lifetime of 11.6 years, if the air conditioner energy efficiency limit can be improved by 1.4% ($\varepsilon = 0.014$) from the current level, CO_2 emissions can be reduced by approximately the same amount as when the average product lifetime is extended to 13.6 years (at the current energy efficiency). If the air conditioner energy efficiency limit is improved further to 5%, 10%, and 15% below the current level, it is possible to achieve CO_2 emissions that are lower than those when the average product lifetime is extended to 13.6 years, by 0.28, 0.67, and 1.05 million tonnes, that is, 2.6%, 6.2%, and 9.8%, respectively.

The model proposed in this study not only estimates the CO_2 emissions derived from residential air conditioners but also offers a target value for energy efficiency that indicates the degree to which energy-saving technology needs to be improved. The above results point to 1.4% as a significant level of energy performance improvement of residential air conditioners. This concrete target value and its justification offer air conditioning manufacturers a clear course of action for how to move forward in cutting CO_2 emissions further, as well as motivation to improve their technology.

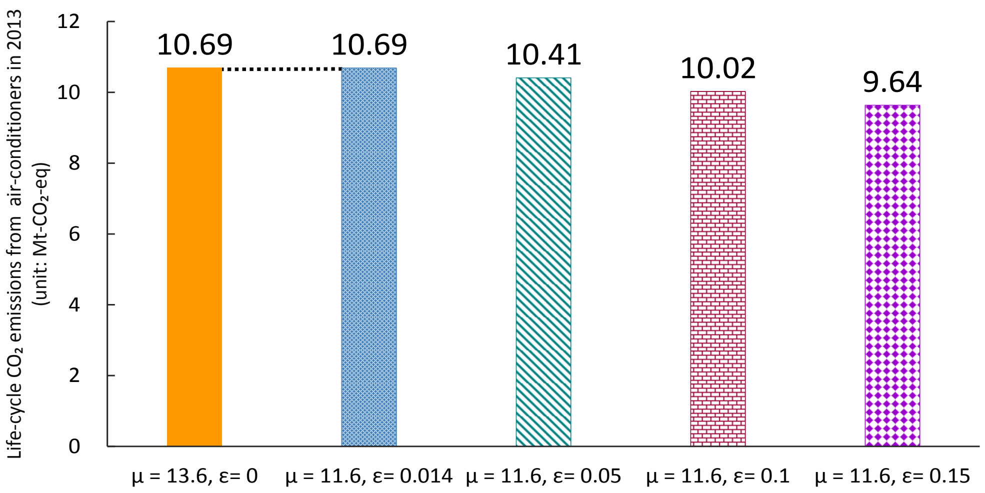

Figure 3.6 Estimated 2013 life-cycle CO_2 emissions for an average product lifetime of 13.6 years, and for an average product lifetime of 11.6 years with 1.4%, 5%, 10%, and 15% reductions in critical value of annual electricity consumption

3.4. Conclusions

In this study, I proposed a model for estimating life-cycle CO_2 emissions that takes into account both the lifetime and energy efficiency of a durable good, and employed the model to analyze the influence of changes in the average product lifetime and energy efficiency of residential air conditioners on the life-cycle CO_2 emissions attributable to such air conditioners in Japan. The results demonstrated that from a baseline scenario, extending the average product lifetime would enable a greater reduction in CO_2 emissions than would reducing the average product lifetime. On the other hand, when I considered potential improvements to energy efficiency, I could show that if the critical (limit) value of electricity consumption were reduced by 1.4% or more, along with shortening the average product lifetime by 1 year, then it would be possible to simultaneously stimulate replacement purchases of air conditioners and reduce life-cycle CO_2 emissions. Specifically, I showed that such changes would have made it possible to simultaneously increase replacement purchases of air conditioners by 6.5% and reduce life-cycle CO_2 emissions by 0.4% in 2013. Although the emission reduction effect under such a combined scenario may be small, both the economic and environmental benefits should be considered in policies.

The model proposed in this study is capable of concretely indicating technological target values that the air conditioning industry should aim for in the effort to cut CO_2 emissions. The model makes it possible to formulate more efficient measures for reducing CO_2 emissions associated with durable goods.

Appendix 3A

Table 3A. Annual new shipments of residential air conditioners in Japan

Year	Annual new shipments of residential air conditioners in Japan	Year	Annual new shipments of residential air conditioners in Japan
1972	1499171	1993	5081736
1973	2152370	1994	7316391
1974	2050003	1995	7988333
1975	2049782	1996	8248031
1976	2249268	1997	6272249
1977	2556023	1998	6724606
1978	3446260	1999	6437707
1979	3470707	2000	7192303
1980	2105361	2001	7521359
1981	2387442	2002	6866051
1982	1917207	2003	6465568
1983	2532550	2004	7036933
1984	3029888	2005	7573317
1985	3674532	2006	7416903
1986	3646413	2007	7382136
1987	4218736	2008	7579023
1988	4552774	2009	6906155
1989	5066673	2010	8338230
1990	6590422	2011	8302926
1991	7364120	2012	8520979
1992	5680544	2013	9422757

Appendix 3B

Table 3B. Annual electricity consumption of an "average" residential air conditioner

Production year	Annual electricity consumption of an "average" residential air conditioner (unit: kWh)
1995	1492
1996	1302
1997	1201
1998	1159
1999	1068
2000	1017
2001	990
2002	947
2003	963
2004	945
2005	919
2006	882
2007	865
2008	858
2009	849
2010	872
2011	845
2012	846
2013	844

Note: The "average" air conditioner is an air conditioner with energy efficiency of 2.8 kW (sufficient to cool a room of approx. 18 m^2).

Appendix 3C

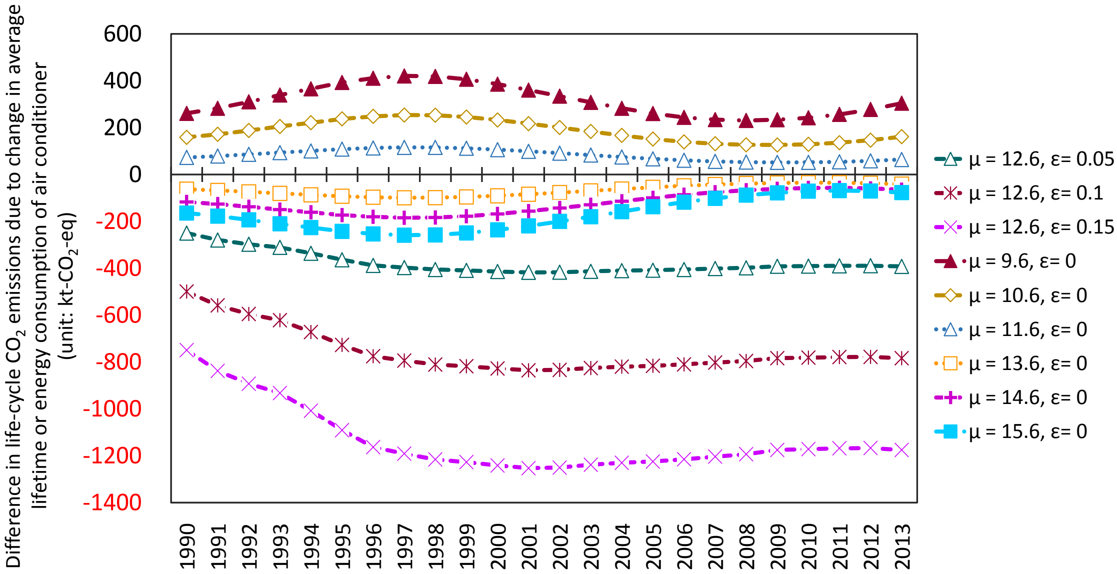

Figure 3A. Difference in life-cycle CO_2 emissions relative to baseline scenario, for each change scenario where average lifetime is ranged from $\mu = 9.6$ to $\mu = 15.6$

Chapter 4 Comprehensive analysis of roles of technology, product lifetime, and energy efficiency for climate mitigation

4.1 Introduction

In chapter 3, I estimated the reduction potential of change in product lifetime and energy efficiency on CO_2 emissions from air conditioners in Japan. I also showed a target value of improvement rate of the energy efficiency for conducting scrappage schemes. However, I could not consider technologies of industries associated with manufacturing and using air conditioners including supply chains in chapter 3. It is indispensable to consider comprehensively CO_2 reduction measures of durable goods including the other industries that are surrounding with air conditioners for realizing effective CO_2 emission reduction. In addition, the target value of improvement rate of energy efficiency in use of air conditioners showed in chapter 3 is for conducting scrappage schemes. More concretely, it is improvement rate necessary for compensating for CO_2 reduction achieved by one year product lifetime extension. On the other hand, CO_2 reduction targets determined in international agreements for climate mitigation such as Kyoto protocol and Paris Agreement are set based on intertemporal CO_2

emissions. Therefore, a target value of improvement rate of energy efficiency of air conditioners corresponding to the CO_2 reduction targets determined in those international agreements is necessary for achieving resolution of global warming.

Some previous studies analyzed environmental burdens from durable goods considering technologies of the other industries than durable goods industries themselves. For example, 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. Estimated the impacts of product lifetime extension of automobiles on income and energy consumption in Japan with a social accounting method.

Those previous studies conducted more comprehensive discussion including technologies of the other industries than durable goods sectors itself such as supply chains. However, they did not discuss CO_2 emission reduction from durable goods simultaneously considering the following three points that are critically important for environmental burdens from durable goods; product lifetime, energy efficiency and industrial technology surrounding durable goods production and use.

Motivated to redress these shortcomings, 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 industrial technology changes surrounding air conditioner production and use, product lifetime changes, and energy efficiency improvements of air conditioners. 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 4.2 explains the methodology, Section 4.3 describes the data, Section 4.4 presents the results, and finally Section 4.5 offers a conclusion.

4.2 Methodology

4.2.1 Estimating life-cycle CO_2 emissions of household air conditioners with environmental input-output framework including effects of change in product lifetime and energy efficiency

I apply an environmental input–output framework to conduct the comprehensive decomposition analysis as I mentioned in section 4.1. In accordance with an environmental input–output analysis (Leontief, 1970; Munksgaard *et al*., 2000; Mongelli *et al*., 2006; Turner *et al*., 2007; Peters, 2008; Andrew *et al*., 2009; Miller and Blair, 2009; Nansai *et al*., 2009, 2015; Müller and Schebek, 2013; Shigetomi *et al*., 2014, 2015), life-cycle CO_2 emissions of household air conditioners at year t in Japan for average lifetime μ and reduction rate of technological critical value of annual electricity consumption ε, $C_t(\mu,\varepsilon)$ can be estimated as follows:

$$C_t(\mu,\varepsilon) = \mathbf{e}_t\left(\mathbf{I}-\mathbf{A}_t\right)^{-1}\mathbf{F}_{t,ac}(\mu,\varepsilon) = \mathbf{e}_t\mathbf{L}_t\mathbf{F}_{t,ac}(\mu,\varepsilon) \quad (4.1)$$

where $\mathbf{e}_t = \left(e_{t,i}\right)$ is the CO_2 emission coefficient row vector expressing the direct

CO_2 emissions per unit production of industry i in year t, $\mathbf{I}$ is an identity matrix, $\mathbf{A}_t = \left(a_{t,ij}\right)$ is the technical coefficient matrix expressing the intermediate input from industry i necessary per unit production of industry j in year t, $\mathbf{L}_t$ is the Leontief inverse matrix expressing the direct and indirect intermediate inputs into industry j from industry i in year t, and $\mathbf{F}_{t,ac}(\mu,\varepsilon)$ is the final demand vector for household air conditioners for a average lifetime μ and a reduction rate of technological critical value of annual electricity consumption ε. Note the definition $\mathbf{L}_t = \left(\mathbf{I}-\mathbf{A}_t\right)^{-1}$.

The final demand for household air conditioners in year t can be formularized as follows:

$$\mathbf{F}_{t,ac}(\mu,\varepsilon) = \begin{bmatrix} 0 \\ \vdots \\ 0 \\ f_{t,ac}(\mu) \\ f_{t,elec}(\mu,\varepsilon) \\ f_{t,tran}(\mu) \\ f_{t,com}(\mu) \\ 0 \\ \vdots \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ \vdots \\ 0 \\ p_{ac}B_t(\mu) \\ \sum_{i=1972}^{t} p_{elec}\lambda_i(\varepsilon)\varphi_{t-i}(\mu)B_i(\mu) \\ p_{tran}B_t(\mu) \\ p_{com}B_t(\mu) \\ 0 \\ \vdots \\ 0 \end{bmatrix} \tag{4.2}$$

where, $f_{t,ac}(\mu)$, $f_{t,tran}(\mu)$, $f_{t,com}(\mu)$ are the final demand of household air conditioners, the transportation margin and commercial margin associated with new purchase of air conditioners in year t on an average lifetime μ respectively, and $f_{t,elec}(\mu,\varepsilon)$ is the electricity demand for operating air conditioners in year t on average lifetime μ and the reduction rate of annual electricity consumption ε.

Here, the final demand for household air conditioners can be calculated by multiplying the production price per air conditioner unit p_{ac} (yen) by the number of new air conditioners sold $B(\mu)$, that is, as $p_{ac}B(\mu)$. The corresponding electricity demand for operating these air conditioners can be calculated by obtaining the electricity consumption for each year of manufacture, by multiplying the number of air conditioners of each year of manufacture that are in use each year $\varphi_{t-i}(\mu)B(\mu)$ by the electricity consumption per unit for each year of manufacture for a reduction rate of technological critical value of annual electricity consumption ε, $\lambda_i(\varepsilon)$ (kWh), and also by the unit price of electricity p_{elec} (yen/kWh), as $p_{elec}\lambda_i(\varepsilon)\varphi_{t-i}(\mu)B_i(\mu)$, and then finally summing over the years of manufacture i. In Eq. (4.2), I can multiply the number of new household air conditioners sold $B_t(\mu)$ by the transportation margin per unit, p_{tran} (yen), and the commercial margin per unit, p_{com} (yen), to obtain the transportation margin and commercial margin, respectively, associated with household air conditioners. Note that the final demand vector expressed by Eq. (4.2) is influenced by changes in both the average lifetime of household air conditioners μ and the reduction rate of the technological critical value of annual electricity consumption ε. In this study, the survival rate of air conditioners $\varphi_{t-i}(\mu)$ follows a Weibull distribution as described in Eq. (3.1) at chapter 3. I also use the calculation methodologies of the number of new air conditioners sold for average lifetime μ, $B_t(\mu)$ $(B_i(\mu))$, and the annual electricity consumption per air conditioner unit manufactured in year i for a reduction rate of technological critical value of annual electricity consumption ε, $\lambda_i(\varepsilon)$, same as chapter 3.

4.2.2 Structural decomposition analysis of the life-cycle CO_2 emissions of household air conditioners

Using Eq. (4.1), for the baseline scenario with average lifetime $\mu = \bar{\mu} = 12.6$ and the relative reduction of the technological limit of annual electricity consumption $\varepsilon = 0$, the difference in CO_2 emissions derived from household air conditioners between year t and year t' $(<t)$, ΔC, can be formularized as

$$
\begin{aligned}
\Delta C &= C_t(\bar{\mu},0) - C_{t'}(\bar{\mu},0) \\
&= \mathbf{e}_t \mathbf{L}_t \mathbf{F}_{t,ac}(\bar{\mu},0) - \mathbf{e}_{t'} \mathbf{L}_{t'} \mathbf{F}_{t',ac}(\bar{\mu},0)
\end{aligned}
\tag{4.3}
$$

Using a structural decomposition analysis (e.g., Ang, 1995, 2004; Lin and Polenske, 1995; Dietzenbacher and Los, 1998; Sun, 1998; Kagawa and Inamura, 2001; Ang *et al.*, 2003, 2009; Hoekstra and van den Bergh, 2003; Dietzenbacher and Stage, 2006; Guan *et al.*, 2008, 2009; Wachsmann *et al.*, 2009; Zhang, 2009; Su and Ang, 2012; Lenzen, 2016), ΔC can be broken down further as follows:

$$
\begin{aligned}
\Delta C = &\frac{1}{6}\Delta\mathbf{e}\left\{2\mathbf{L}_{t'}\mathbf{F}_{t',ac}(\bar{\mu},0) + \mathbf{L}_t\mathbf{F}_{t',ac}(\bar{\mu},0) + \mathbf{L}_{t'}\mathbf{F}_{t,ac}(\bar{\mu},0) + 2\mathbf{L}_t\mathbf{F}_{t,ac}(\bar{\mu},0)\right\} \\
&+\frac{1}{6}\left\{2\mathbf{e}_{t'}\mathbf{L}_t\Delta\mathbf{A}\mathbf{L}_{t'}\mathbf{F}_{t',ac}(\bar{\mu},0) + \mathbf{e}_t\mathbf{L}_t\Delta\mathbf{A}\mathbf{L}_{t'}\mathbf{F}_{t',ac}(\bar{\mu},0) + \mathbf{e}_{t'}\mathbf{L}_t\Delta\mathbf{A}\mathbf{L}_{t'}\mathbf{F}_{t,ac}(\bar{\mu},0) + 2\mathbf{e}_t\mathbf{L}_t\Delta\mathbf{A}\mathbf{L}_{t'}\mathbf{F}_{t,ac}(\bar{\mu},0)\right\} \\
&+\frac{1}{6}\left\{2\mathbf{e}_{t'}\mathbf{L}_{t'} + \mathbf{e}_t\mathbf{L}_{t'} + \mathbf{e}_{t'}\mathbf{L}_t + 2\mathbf{e}_t\mathbf{L}_t\right\}\Delta\mathbf{F}_{ac}
\end{aligned}
\tag{4.4}
$$

where $\Delta\mathbf{e} = \mathbf{e}_t - \mathbf{e}_{t'}$, $\Delta\mathbf{A} = \mathbf{A}_t - \mathbf{A}_{t'}$ and $\Delta\mathbf{F}_{ac} = \mathbf{F}_{t,ac}(\bar{\mu},0) - \mathbf{F}_{t',ac}(\bar{\mu},0)$. The first, second, and third terms on the right-hand side of Eq. (4.4) express respectively the impacts of changes in the direct CO_2 emission coefficient row vector, the technical coefficient matrix, and the final demand vector for household air conditioners on CO_2

emissions derived from household air conditioners.

In accordance with Kagawa *et al.* (2008), the changes in direct CO_2 emission coefficient and technical coefficient in an arbitrary industry j can respectively be expressed as

$$\Delta \mathbf{e}_j = \begin{bmatrix} 0 & \cdots & \quad & \cdots & \quad \end{bmatrix} \tag{4.5}$$

$$\Delta \mathbf{A}_j = \begin{bmatrix} 0 & \cdots & & & & \cdots & \\ 0 & \cdots & & & & \cdots & \\ \vdots & \ddots & \vdots & \vdots & \vdots & \iddots & \vdots \\ 0 & \cdots & & & & \cdots & \\ \vdots & \iddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & \cdots & & & & \cdots & \\ 0 & \cdots & & & & \cdots & \end{bmatrix} \tag{4.6}$$

where m is the number of industrial sectors. If I substitute Eqs. (4.5) and (4.6) into the structural decomposition equation, Eq. (4.4), I obtained the following detailed structural decomposition equation:

$$
\begin{aligned}
\Delta C &= \frac{1}{6}\sum_{j=1}^{m}\Delta \mathbf{e}_j \left\{2\mathbf{L}_{t'}\mathbf{F}_{t',ac}(\bar{\mu},0)+\mathbf{L}_{t}\mathbf{F}_{t',qc}(\bar{\mu},0)+\mathbf{L}_{t'}\mathbf{F}_{t,ac}(\bar{\mu},0)+2\mathbf{L}_{t}\mathbf{F}_{t,ac}(\bar{\mu},0)\right\} \\
&+\frac{1}{6}\sum_{j=1}^{m}\left\{2\mathbf{e}_{t'}\mathbf{L}_{t}\Delta\mathbf{A}_j\mathbf{L}_{t'}\mathbf{F}_{t',ac}(\bar{\mu},0)+\mathbf{e}_{t}\mathbf{L}_{t}\Delta\mathbf{A}_j\mathbf{L}_{t'}\mathbf{F}_{t',ac}(\bar{\mu},0)+\mathbf{e}_{t'}\mathbf{L}_{t}\Delta\mathbf{A}_j\mathbf{L}_{t'}\mathbf{F}_{t,ac}(\bar{\mu},0)+2\mathbf{e}_{t}\mathbf{L}_{t}\Delta\mathbf{A}_j\mathbf{L}_{t'}\mathbf{F}_{t,ac}(\bar{\mu},0)\right\} \qquad (4.7) \\
&+\frac{1}{6}\left\{2\mathbf{e}_{t'}\mathbf{L}_{t'}+\mathbf{e}_{t}\mathbf{L}_{t'}+\mathbf{e}_{t'}\mathbf{L}_{t}+2\mathbf{e}_{t}\mathbf{L}_{t}\right\}\Delta\mathbf{F}_{ac}
\end{aligned}
$$

4.2.3 Scenario analysis of effect of change in product lifetime and energy efficiency of air conditioners on the life-cycle CO_2 emissions

We also conduct a scenario analysis of effects of change in product lifetime and energy efficiency of air conditioners in Japan for evaluating CO_2 emission reduction potential of those changes. The effects of product lifetime change from $\mu = 12.6$ to $\mu*$ and a $(100\times\varepsilon)$% reduction of energy efficiency of air conditioners from current level on the CO_2 emissions from year t to year t', $\Delta C(\mu*, \varepsilon)$, can be calculated with Eq. (4.1) as follows.

$$
\begin{aligned}
\Delta C(\mu*, \varepsilon) &= C_t(\bar{\mu}, 0) - C_{t'}(\mu*, \varepsilon) \\
&= \mathbf{e}_t\mathbf{L}_t\mathbf{F}_{t,ac}(\bar{\mu}, 0) - \mathbf{e}_{t'}\mathbf{L}_{t'}\mathbf{F}_{t',ac}(\mu*, \varepsilon)
\end{aligned} \qquad (4.8)
$$

In this study, I estimated the change in CO_2 emissions of air conditioners due to change in product lifetime and energy efficiency from 1990 and 2005. I calculate the CO_2

emission change for different values of $\mu*$ and ε using Eq. (4.8). I follow the same methodologies of changing average lifetime and energy efficiency as explained section 3.2.4 in chapter 3.

4.3 Data

In this study, I performed an analysis using 1990–1995–2000–2005 linked environmental input–output tables for Japan (397 sectors), based on producer's prices for 2005, as estimated by Nansai *et al*. (2009).

I determined the producer's price per household air conditioner unit, p_{ac}, to be an average of 66,842 yen/unit, by calculating a weighted average of air conditioner prices based on production output and performance values from an input–output table for 2005 in Japan. In addition, by dividing the production output of household air conditioner parts, fittings, and accessories, recorded in a 2005 input–output table, by the total production of air conditioners, I calculated the expense of parts, fittings, and accessories per household air conditioner unit and added this installation expense to the average air conditioner price determined earlier to arrive at a total household air conditioner producer's price p_{ac} of 77,024 yen. For the electricity price p_{elec}, I used 16.15 yen/kWh, which is the weighted average price of electric power for the commercial sector based on production output and power generation methods, according to the Japanese 2005 input–output table.

To obtain the transportation margin p_{tran} and commercial margin p_{com} for the household air conditioner sector, I divided the transportation margin and commercial margin for the household air conditioner sector given in the Japanese 2005 input–output table by the number of new household air conditioner units sold in 2005, $B_{2005}(\bar{\mu})$, published by the Japan Refrigeration and Air Conditioning Industry Association (JRAIA).

I obtained the direct CO_2 emission coefficient vector $\mathbf{e}_t$ from the Japanese 1990–1995–2000–2005 linked environmental input–output tables for Japan, based on the producer's price for 2005, as estimated by Nansai *et al*. (2009).

4.4 Results

4.4.1. Decomposition effects

Figure 4.1 shows the results of decomposition on the change in CO_2 emissions associated with final demand for household air conditioners for the 5-year periods from 1990 to 1995, from 1995 to 2000, and from 2000 to 2005, as well as for the period from 1990 to 2005, due to five primary factors: (1) change in the direct CO_2 emission coefficient in the household air conditioner sector, (2) changes in the direct CO_2 emission coefficients in other sectors, (3) change in the technical coefficients in the household air conditioner sector, (4) changes in the technical coefficients in other sectors, and (5) change in the final demand related to household air conditioners (purchase and use of air conditioners). From Fig. 4.1, we can see that for the 15-year period from 1990 to 2005, total emissions of CO_2 derived from household air conditioners increased by 1.47 Mt-CO_2, which corresponds to an increase of 16.5% relative to the 1990 level of emissions.

Looking at the results of this structural decomposition analysis, focusing on the period from 1990 to 2005, we can see that the change in final demand related to household air conditioners, including air conditioner purchase and electricity consumption in using air conditioners, contributes 3.57 Mt-CO_2 of emissions, which represents a major factor in global warming. On the other hand, the change in technical coefficient in the household air conditioner sector and changes in the direct CO_2 emission coefficients in other sectors both tend to reduce emissions, making contributions of −1.22 and −0.69 Mt-CO_2, respectively. The contributions of the change in direct CO_2 emission coefficient of the household air conditioner and the changes in technical coefficients in other sectors were −0.12 and 0.07 Mt-CO_2, respectively, which both represent very small impacts on emissions over the 15-year period.

Looking at the role played by final demand associated with household air conditioners on global warming, we can see that over the 5-year period from 1990 to 1995, the change in final demand drove up emissions by a remarkable 3.11 Mt-CO_2, a huge contribution to global warming (see Fig. 4.1). However, over the two periods from 1995 to 2000 and from 2000 to 2005, although the change in final demand still contributed to increasing emissions, the impact was very small. The contributions to increasing emissions were only 0.57 and 0.04 Mt-CO_2, respectively, in the two periods.

From these results, I can conclude that over the 10-year period from 1995 to 2005, the role played by final demand associated with household air conditioners on global warming diminished greatly.

Interestingly, over the 10-year period from 1990 to 2000, the changes in the direct CO_2 emission coefficients of the other industrial sectors (except for household air conditioner sector) had the overall effect of reducing CO_2 emissions, but conversely, in the 5-year period from 2000 to 2005, this same factor made a strong contribution to increasing emissions, by 1.64 Mt-CO_2. That is, this factor played a crucial role in global warming than final demand related to the household air conditioner sector (purchase and use of air conditioners) in the 5-year period. (see Fig. 4.1). This result indicates that in terms of reducing CO_2 emissions derived from household air conditioners, promoting demand for replacement air conditioners that consume less electricity is important from an economic perspective, but also indicates that it is important to take measures to reduce CO_2 emissions from other upstream industries that produce the materials and parts necessary for manufacturing air conditioners.

Change in the technology of the household air conditioner industry contributed to reducing CO_2 emissions consistently throughout the period from 1990 to 2005 (Fig. 4.1), which indicates that a strong effort was made to reduce CO_2 emissions by improving technology used in the manufacture of household air conditioners. The CO_2 reduction by technological change in the "Household air-conditioner sector" accounted for 62% of the total emissions reduction from the technological change of all industries.

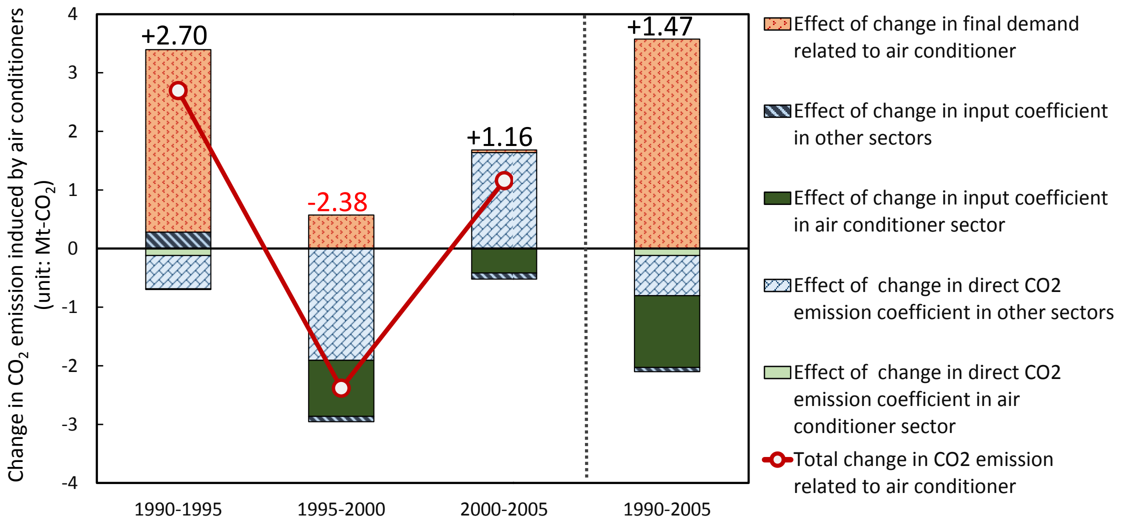

Figure 4.1 Structural decomposition results of CO_2 emissions associated with household air conditioners in Japan between 1990 and 2005

4.4.2 Industrial emission intensity effects

As described in the previous section, it is important to curb the emissions of CO_2

associated with the production of goods and services necessary for the manufacture and use of household air conditioners. Figure 4.2 shows a ranking of industrial sectors in terms of how much impact the change in the direct CO_2 emission coefficient of each sector had on CO_2 emissions derived from household air conditioners over the 15-year period from 1990 to 2005. The 10 sectors that contributed most to increasing and reducing emissions are listed. Figure 4.2 shows that the change in the direct CO_2 emission coefficient of the "Electricity sector" made the biggest contribution to reducing emissions. The sector that contributed most to increasing emissions between 1990 and 2005 was "On-site power generation sector." The change in the emission coefficient of this sector made a contribution of +137 kt-CO_2. The next highest ranking sectors were "Pig iron", at +52 kt-CO_2, and "Air transport", at +23 kt-CO_2.

In the period from 1990 to 2005, the net effect of the changes in direct CO_2 emission coefficients was −804 kt-CO_2, a net reduction in CO_2 emissions derived from household air conditioners. In the most recent 5-year period, from 2000 to 2005, however, the net impact of the changes was a substantial increase in CO_2 emissions (1633 kt-CO_2), so clearly reducing the direct CO_2 emission coefficient of the supply chain for household air conditioners plays an important role in mitigating global warming.

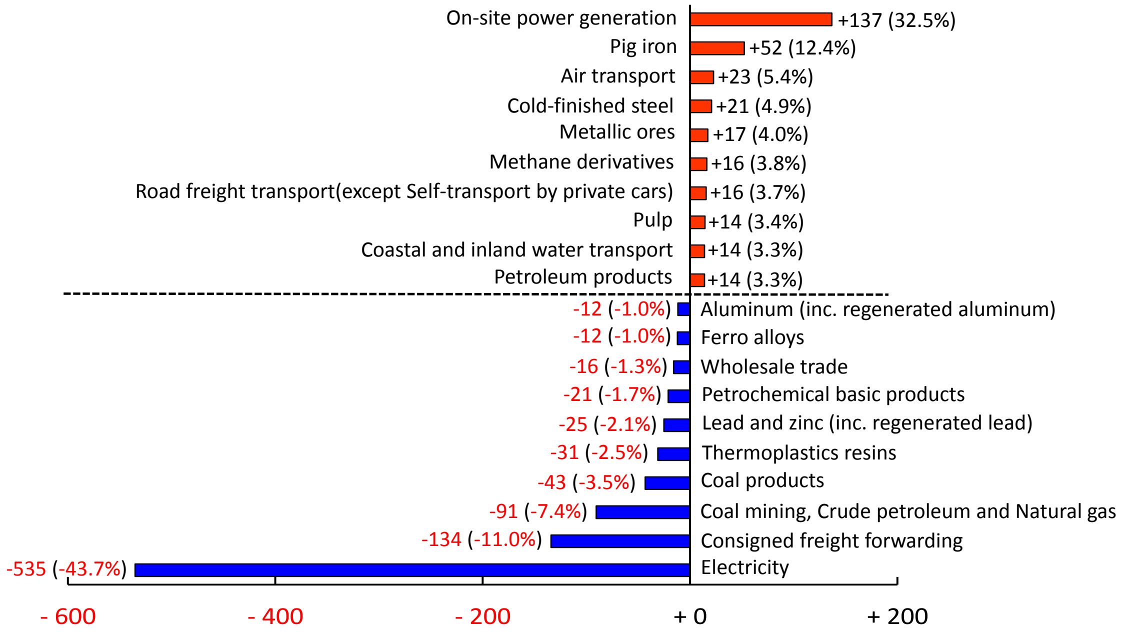

Figure 4.2 Impact of changes in direct CO_2 emission coefficients of different industrial sectors on CO_2 emissions derived from household air conditioners between 1990 and 2005 (The percentages mean ratios of each effect in total emissions increase or reduction.)

4.4.3 Industrial technology effects

Figure 4.3 shows the impact of the technological change in each industrial sector on the CO_2 emissions derived from household air conditioners over the period from 1990 to 2005, listing the 10 sectors that contributed the most to increasing and reducing emissions. The change in the “Integrated circuits sector” was by far the biggest contributor to reducing emissions (−326 kt-CO_2), followed in order by “Coal mining, Crude petroleum, and Natural gas” (−122 kt-CO_2).

At the same time, Fig. 4.3 reveals that the impact of technological change in the three sectors “Retail trade”, “Electricity”, and “Liquid crystal elements”, amounting to +174, +91, and +55 kt-CO_2, respectively, had the effect of dampening the emissions-cutting effect of technological improvement in the “Household air conditioner sector”. Here it is necessary for household air conditioner sector to cooperate with these sectors when trying to reduce the CO_2 emissions generated in association with air conditioner manufacture and use. However, any policies or measures aimed at reducing emissions that link the technologies of these sectors require considerable time, effort, and money, making them difficult to realize in practice.

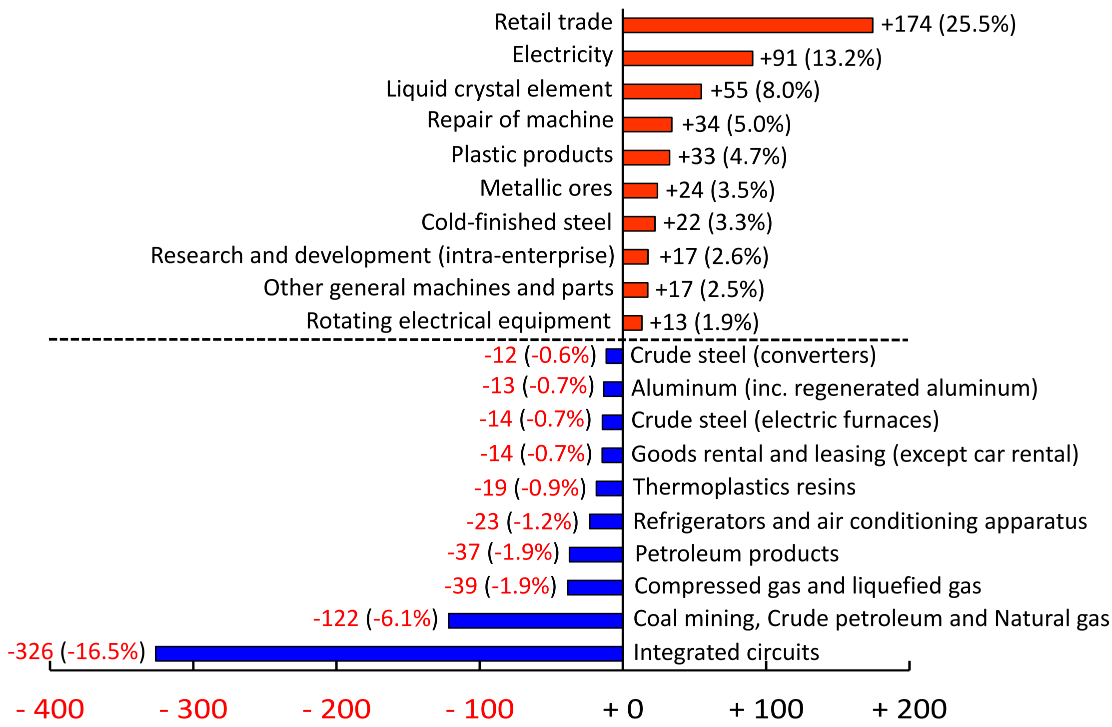

Figure 4.3 Impact of changes in technology coefficients in different industrial sectors on CO_2 emissions derived from household air conditioners between 1990 and 2005 (The percentages mean ratios of each effect in total emissions increase or reduction.)

4.4.4 Role of product lifetime and energy efficiency in CO_2 emissions

Therefore, it is clearly worth examining two highly effective approaches to reducing emissions. The first is reducing CO_2 emissions by shortening the service life (use time) of older household air conditioners requiring relatively high electricity consumption, that is, shortening product lifetime. In this case, CO_2 emissions during operation are reduced because old air conditioners are replaced by new, more energy-efficient air conditioners sooner. However, the number of new household air conditioners that are manufactured increases, thereby increasing CO_2 emissions in manufacturing.

The second countermeasure is to improve the energy efficiency (i.e., reduce electricity consumption) of household air conditioners during operation. As the electricity consumption of household air conditioners during operation declines in response to technological advances, CO_2 emissions arising from the use of air conditioners naturally decrease. It would be useful, then, to analyze how effective each of these two measures is in terms of reducing CO_2 emissions derived from household air conditioners, and also how much CO_2 emissions a combination of these two measures could reduce.

Figure 4.4 shows the CO_2 potential of product lifetime change and technological limit improvement of annual electricity consumption. The vertical axis of Fig. 4.4 represents the reduction rate of the critical value of annual electricity consumption ε, while the horizontal axis represents the change in average product lifetime relative to the baseline average lifetime, 12.6 years, $\Delta\mu$. A deeper shade of blue indicates a greater reduction in emissions due to the changes in average lifetime and in the critical value of electricity consumption. Conversely, a deeper shade of red indicates a greater increase in emissions.

From Fig. 4.4, we see that the further we go towards the top right of Fig. 4.4, the deeper the blue, that is, the greater the reduction in CO_2 emissions derived from household air conditioners. Therefore, as the product lifetime is extended and electricity consumption is reduced, a reduction in emissions is realized. Considering the distribution of colors in this color map, it appears that improving electricity consumption might be more effective than extending product lifetime for achieving a particular reduction in CO_2 emissions. When product lifetime is extended, the reduction in CO_2 emissions due to manufacturing fewer new air conditioners is offset by the increase in emissions due to the increased operation time of older air conditioners. On the other hand, since improving electricity consumption does not lead to more emissions during manufacture, it is a more sure and effective way of reducing CO_2 emissions.

In order to have maintained the CO_2 emissions derived from household air conditioners in 2005 at their 1990 level for the current average lifetime (i.e., $\Delta\mu = 0$), it would have been necessary to reduce the technological critical value of energy performance by a further 19.1% below its current level ($\varepsilon = 0.191$) (see Fig. 4.4). In this way, to maintain the 1990 level of emissions without adopting measures to shorten air conditioner lifetime (i.e., measures to stimulate demand for new air conditioners), it would have been necessary for the air conditioner industry to improve its energy performance by about 19% over the current energy performance target ($\hat{K} = 824$ kWh; see Fig. 3.1). If air conditioner lifetime were shortened by 1 year and measures were taken to stimulate demand for new air conditioners having relatively low electricity consumption, in order to maintain emissions in 2005 at the 1990 level, it would have been necessary to improve the energy performance target by 20.6%. Conversely, if air conditioner lifetime were extended by 1 year and measures were taken to prolong possession period of air conditioners, it would have been necessary to improve the energy performance target by only 17.8% in order to maintain emissions in 2005 at the 1990 level.

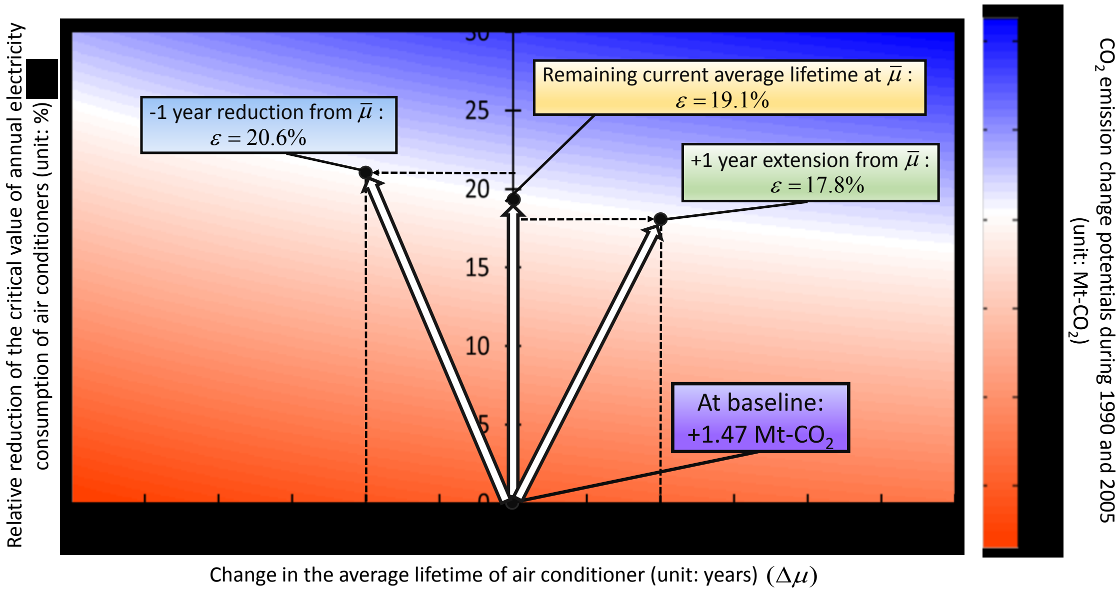

Figure 4.4 CO_2 emission change potentials for the period from 1990 to 2005 under the combined scenario of average lifetime change and limit electricity consumption change (unit: Mt-CO_2)

(The values of ε written in the boxes express relative reduction of the critical value of annual electricity consumption necessary for maintain CO_2 emissions in 2005 at 1990 level on each lifetime scenario)

4.5 Conclusion and Policy Implications

In this study, using a structural decomposition analysis, I analyzed the main factors influencing the change in CO_2 emissions derived from household air conditioners in

Japan between 1990 and 2005. In addition, I clearly identified the product lifetime of household air conditioners and the degree of improvement in their energy efficiency (electricity consumption) that would have been necessary to maintain CO_2 emissions in 2005 at the 1990 level.

Firstly, I found that the CO_2 emissions derived from the manufacture and use of household air conditioners increased by 1.47 Mt-CO_2 between 1990 and 2005. An important point is that, although on the one hand technological improvement in the household air conditioner sector accounted for a reduction of 1,342 kt-CO_2 in emissions, at the same time, other sectors providing goods and services necessary for the manufacture and sale of household air conditioners, such as retail trade and liquid crystal elements, contributed substantially to increasing emissions. Although it is definitely important to try to reduce emissions across the entire supply chain of the household air conditioner sector, it should also be understood that emission reduction measures that link the technologies of different industries require considerable time, effort, and expense.

Technology policy that focuses on improving industrial technology is important, but so too is policy that stimulates demand for replacing durable consumer goods sooner with new, more energy-efficient models (i.e., measures that shorten product lifetime). In this study, I determined that if the average lifetime of household air conditioners sold in Japan between 1972 and 2005 had been shortened by 1 year, then assuming an average annual production of 5 million units (total cumulative sales between 1972 and 2005 = 171 million / 33 years), maintaining CO_2 emissions at the 1990 level would have required approximately a further 20.6% reduction in the energy efficiency (electricity consumption) improvement target, from 824 to 654 kW. Since annual electricity consumption of air conditioners has been hardly improved recently (Agency for Natural Resources and Energy, 2010, 2011, 2012, 2013, 2014), however, the further reduction may be difficult for air conditioner industry. We should another measure, which is to promote extension of using air conditioners and lighten the improvement target. In this case, I showed the energy performance target as 17.8% if average lifetime of air conditioners was extended by 1 years. In light of this analysis of the environmental impact of new product penetration and energy efficiency (electricity consumption) improvement, the government and air conditioner industry need to urgently institute measures to cut CO_2 emissions.

There are two conceivable approaches to achieving reductions in the CO_2 emissions derived from durable consumer goods: adopting policies that promote earlier replacement and at the same time set higher minimum energy efficiency standards for products, or adopting policies to promote later replacement and at the same time reducing the burden of meeting energy efficiency standards. Obviously, these are completely opposite in their orientation. In this study, I quantitatively demonstrated the combination of product lifetime and energy efficiency target improvement rate necessary to maintain CO_2 emissions at the 1990 level, and this result is useful in determining which of the two above approaches is best.

Chapter 5 Conclusion

This doctoral dissertation focused on CO_2 emissions derived from air conditioners in Japan as a case study and discussed how we should reduce the CO_2 emissions from viewpoints of product lifetime, energy efficiency, and industrial technologies surrounding air conditioners in Japan.

In chapter 3, I statistically modeled product lifetime and trend of energy efficiency of air conditioners in Japan by Weibull distribution function and reverse logistic function respectively. After that, I estimated CO_2 emissions derived from air conditioners in Japan using those models of product lifetime and energy efficiency and evaluated the impacts of changes in product lifetime and energy efficiency of air conditioners on the CO_2 emission in Japan. I compared the total CO_2 emissions when product lifetime is shortened and extended by 1 year respectively and found that extending product lifetime can reduce the CO_2 emissions rather than shortening product lifetime. I also estimated total CO_2 emissions when energy efficiency improves by 5%, 10%, and 15% and also found that total CO_2 emissions when energy efficiency improve by 5% is lower than those when product lifetime is extended by 1 year and energy efficiency improvement seems to reduce more CO_2 emissions than product lifetime extension. Moreover, I focused on CO_2 emission increase due to shortening product lifetime caused by scrappage schemes and conducted combined scenario analyses about changes in product lifetime and energy efficiency for estimating a target value of energy efficiency improvement to conduct scrappage schemes. I showed that even if product lifetime becomes 1 year shorter due to conducting scrappage schemes, by 1.4% improvement of energy efficiency from the current level, we can obtain the same CO_2 emission reduction as product lifetime extension by 1 year.

In chapter 4, I connected both the models of product lifetime and energy efficiency in chapter 3 with environmental input-output model and constructed a comprehensive analytical framework for CO_2 emissions induced by air conditioners in Japan during a period from 1990 to 2005. I applied a structural decomposition analysis and combined scenario analyses for discussing how we should reduce the CO_2 emissions in terms of product lifetime, energy efficiency, and industrial technologies surrounding air conditioner production and use. From the results by structural decomposition analysis, I could find that while air conditioner sector itself had contributed to reducing the CO_2 emissions, the other industrial sectors such as retail trade sector and pig iron sector had contributed to increasing the CO_2 emissions during the period in Japan. Through the combined scenario analysis, I showed the improvement rate of energy efficiency necessary for holding the CO_2 emissions in 2005 at those in 1990. Concretely, if the product lifetime was shortened by 1 year, energy efficiency improvement by 20.6% would have been necessary for maintain the CO_2 emissions in 2005 at the 1990 level. Conversely, if the product lifetime was extended by 1 year, energy efficiency improvement by 17.8% would have been necessary for maintain the CO_2 emissions in 2005 at the 1990 level.

As I mentioned above, this doctoral dissertation shows CO_2 reduction potential of product lifetime change and energy efficiency improvement, quantitative target values of improvement rate of energy efficiency necessary for each corresponding CO_2 reduction target, and contribution of each industry sector to CO_2 emissions derived from air conditioners. These findings in this dissertation are very important information for discussing about the CO_2 reduction policies. In that point, this doctoral dissertation can contribute to developing discussion for reducing CO_2 emissions derived from air conditioners in Japan. The analysis framework presented in this dissertation is not limited to air conditioners; it can be applied to other durable consumer goods such as automobiles, TVs, and refrigerators. In any case, it can serve as a useful framework for formulating policies and measures for reducing CO_2 emissions in connection with durable consumer goods and consumer lifestyles.

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