Journal of Cleaner Production 145 (2017) 172–179

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Dynamic analysis of global warming impact of the household refrigerator sector in Japan from 1952 to 2030

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A R T I C L E I N F O

Article history:
Received 27 October 2016
Received in revised form
10 January 2017
Accepted 10 January 2017
Available online 12 January 2017

Keywords:
Dynamic analysis
Global warming impact
Household refrigerator
Energy consumption
Chemical substitution

A B S T R A C T

The household refrigerators consume large amounts of energy and emit vast refrigerants which contribute to global warming indirectly and directly. The intervention of energy efficiency standard, aging process, and refrigerants substitution result in the performance of the household refrigerator sector varying with time. The present study analyzed dynamic global warming impact of the household refrigerator sector in Japan from the 1950s to 2030 taking into account both the energy effect and chemical effect. The energy effect modelling integrated energy efficiency improvement over year and energy efficiency deterioration over age. The chemical effect modelling involved substitution of three generations of refrigerants on the basis of the flow and stock model. The results showed that the global warming impact of the household refrigerator sector peaked at 25,104 kt CO_2 eq. in 1990 and then decreased to 6506 kt CO_2 eq. in 2030. The energy effect accounted for at least 91% and this ratio would be much higher in the future. Both implementation of minimum energy efficiency programs and substitution of refrigerants reduced the global warming impact significantly. This dynamic analysis could provide a holistic picture of the global warming impact of the household refrigerator sector both retrospectively and prospectively from accessing to the market, through rapid growth, to saturation.

1. Introduction

Global warming, responsible for extreme weather in recent years (Wu et al., 2013), is an ever-increasing environmental problem with far reaching effects (Huisingh et al., 2015). Controlling global temperature increase below 2 °C above the pre-industrial level was strongly recommended by the fourth report of the International Panel on Climate Change (IPCC, 2007), which is a great challenge facing our society. Reduction of greenhouse gas emissions is at the top of the environmental policy agenda today (Weidema et al., 2008).

The household refrigerators are one of the most energy consuming home appliances and thus emit enormous amounts of greenhouse gases indirectly (Kim et al., 2006). On the other hand, the direct emissions of refrigerants which serve as working fluids in household refrigerators may also cause global warming. The minimum energy efficiency standards in Japan (METI, 2015) together with technology advancement promote the improvement of energy efficiency over year. In contrast, the aging of refrigerators will deteriorate the energy efficiency over age. Furthermore, the refrigerant substitution over time also affects the performance of the household refrigerator sector. All these factors result in the global warming impact of the household refrigerators varying with time. However, dynamic analysis is very limited although it could provide insights into the changing features of global warming impact of one sector. In fact, different sectors have distinct characteristics and require particular coping approaches. Hence, it is necessary to investigate the dynamic global warming impact at sector level in order to identify specific measures for global warming mitigation.

There are four mostly used environmental metrics for evaluation of global warming impact: global warming potential (GWP), total equivalent warming impact (TEWI), life cycle climate performance (LCCP), and carbon footprint (CF) (Wu et al., 2013). The GWP is a general index measuring the cumulative radiative forcing value of a greenhouse gas over a defined time horizon relative to CO_2. The TEWI is developed as an index for refrigeration system combining both the direct refrigerant emissions and indirect greenhouse gas emissions from generation of energy for running the equipment

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http://dx.doi.org/10.1016/j.jclepro.2017.01.059
0959-6526/

(Fischer, 1993). As an extension of TEWI, the LCCP is introduced to assess the global warming impact of a refrigerant through its lifetime (Hwang, 2016). By applying life cycle thinking to global warming, the CF describes the greenhouse gas emissions of a product or process not limited to refrigeration system (Alvarez et al., 2016; Čuček et al., 2012). The system boundary for calculating CF varies (Pandey et al., 2011): (i) only accounting for all direct emissions (direct CF); (ii) direct emissions and embodied emissions in purchased energy (basic CF); and (iii) direct emissions and all indirect emissions (full CF). The direct emissions and embodied emissions in purchased energy dominate the total global warming impact and the rest part is much less than the uncertainty in calculating the full CF. It is also an important question that to what extent control over emissions can be made beyond basic CF (Pandey et al., 2011). So the present study analyzed the indirect emissions of greenhouse gas from generation of energy for operating the equipment through its lifetime (energy effect) and the direct emissions of refrigerants during the use and end-of-life disposal stages (chemical effect).

The aim of this study is to understand the global warming impact of the household refrigerator sector in Japan facilitating the decision-making for global warming mitigation. The novelty of this study is that it enables to investigate the global warming impact considering the energy efficiency improvement driven by technology development, energy efficiency deterioration driven by aging process, age composition determined by lifespan distribution, and substitution of different generations of refrigerants. The reminder of this paper is structured as follows: Section 2 presents methods for modelling energy consumption and refrigerant emission. Section 3 discusses the energy effect, chemical effect, and total global warming impact of the household refrigerator sector. Lastly, Section 4 comes to the conclusions.

2. Materials and methods

2.1. Dynamic energy consumption model

The governmental regulations and voluntary activities from the refrigerator sector drive the advancement of cooling, insulation, and control technologies (METI, 2006). Efficient compressor and heat exchanger, improved configuration and insulation material, and optimized cooling circuit and control algorithm all together improve the energy efficiency of refrigerators substantially over year (Metz et al., 2005). On the contrary, there is an aging process during the course of using. The energy efficiency of refrigerators deteriorates as a result of insulation foam aging, dirty coils, and worn out gaskets over age (Kim et al., 2006).

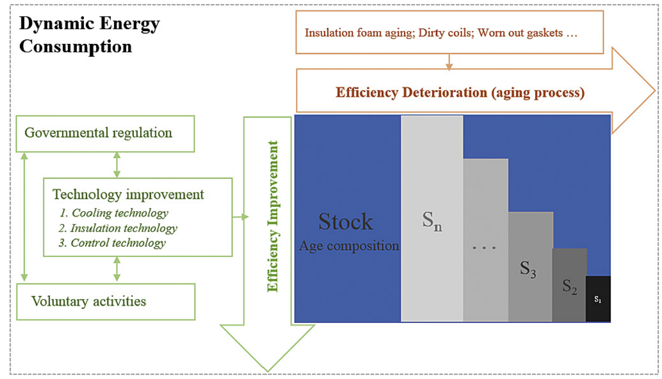

Fig. 1. Dynamic energy consumption model for household refrigerators.

For a specific year, the refrigerators as stock in the household sector were manufactured in different years with different energy efficiencies. Also, refrigerators would consume more and more energy with the increase of age. When the lifespan distribution of refrigerators was determined, the age composition in each year could be obtained according to the new refrigerator inflows into the market. The dynamic energy consumption model considered the energy efficiency improvement driven by technology advancement, energy efficiency deterioration due to aging process, and age composition determined by lifespan distribution, as shown in Fig. 1. This method enables to integrate dynamic factors into estimation of energy consumption of the household refrigerator. The energy consumption and the subsequent global warming information can contribute to the decision-making for relevant stakeholders including the government departments, industry, consumers, etc.

The total energy consumption can be calculated as follows:

$$\begin{bmatrix} E_{1952} \\ E_{1953} \\ \vdots \\ E_t \\ \vdots \\ E_{2030} \end{bmatrix} = \begin{bmatrix} N_{1952} & N_{1953} & \cdots & N_t & \cdots & N_{2030} \end{bmatrix} \times \begin{bmatrix} \left(1-P_{(1952,1952)}\right)\cdot A_{(1952,1952)} & \left(1-P_{(1953,1952)}\right)\cdot A_{(1953,1952)} & \cdots & \left(1-P_{(t,1952)}\right)\cdot A_{(t,1952)} & \cdots & \left(1-P_{(2030,1952)}\right)\cdot A_{(2030,1952)} \\ & \left(1-P_{(1953,1953)}\right)\cdot A_{(1953,1953)} & \cdots & \left(1-P_{(t,1953)}\right)\cdot A_{(t,1953)} & \cdots & \left(1-P_{(2030,1953)}\right)\cdot A_{(2030,1953)} \\ & & \ddots & \cdots & \cdots & \cdots \\ & & & \left(1-P_{(t,t_0)}\right)\cdot A_{(t,t_0)} & \cdots & \cdots \\ \vdots & & & & \ddots & \cdots \\ 0 & & \cdots & & & \left(1-P_{(2030,2030)}\right)\cdot A_{(2030,2030)} \end{bmatrix} \quad (1)$$

where E_t is energy consumption of the refrigerator sector in year t. N_t is the number of refrigerators entering the refrigerator sector in year t. $P_{(t,t0)}$ is the possibility that the refrigerators are abandoned in