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Article

The Life Cycle CO_2 ($LCCO_2$) Evaluation of Retrofits for Water-Saving Fittings

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Abstract: As part of measures being taken against global warming, the reduction of CO_2 emissions by retrofitting for water-saving fittings in homes is spreading throughout the world. However, although this retrofitting reduces the environmental impact at the use stage, it generates new impacts at the production and disposal stages. In addition, there has been little research that discusses the reduction in environmental impact obtained by retrofitting from the viewpoint of the overall life cycle of such fittings. In this paper, an evaluation of the environmental impact of retrofitting in terms of the entire life cycle was carried out for toilet bowls and showerheads. The findings show that even for a toilet bowl that generates a large environmental load at the production stage, there is no overall increase in the environmental impact by retrofitting for the average usable life of 20 years.

Keywords: global warming; CO_2 reduction; water; saving-water; retrofit

1. Introduction

In recent years, studies related to water use, energy consumption, and CO_2 emissions have been conducted globally; and targets for CO_2 emission factors or energy consumption rates of water have been established in several countries, including Australia Britain, Japan, and Taiwan [1–4]. Furthermore, it has been clarified that water use-origin CO_2 emissions by housing fittings such as toilets and showers account for several percent of the total CO_2 emission of each country [5,6]. Owing to the progress made in such environmental research, water-saving labeling and subsidies to accelerate the retrofitting of old fittings for water-saving ones have been realized in many countries. Furthermore, a carbon credit project

based on retrofitting with water-saving fitting has been launched in Japan. In addition, a bilateral offset credit system has been examined with China and Vietnam [5,7–9].

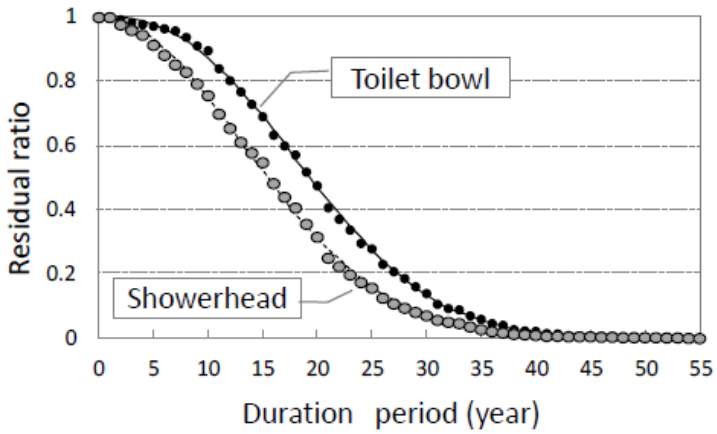
The environmental impact differs greatly depending on the fitting, with there being a great difference in impact for a 25 kg ceramic toilet bowl, which is fired in a kiln at about 1200 °C for 24 h, and a 200 g showerhead produced by plastic injection molding.

From a viewpoint of the whole life cycle of a product, the environmental impact improvement by retrofit is reduced by the load of production stage. Although there is some $LCCO_2$ evaluation research into housing construction [10–12], there is no research which discusses the environmental effect of the retrofit through the whole life cycle.

The timing for the retrofit of fittings varies from less than 10 years to up to 30 years. The duration distributions of toilet bowls and showerheads, as reported in a previous paper, are shown in Figure 1 [13].

The environmental efficiencies of household fittings improve every year. In consideration of this, the influence of a retrofit in terms of the environmental impact for the entire life cycle of a fitting was evaluated, and suitable duration times to minimize the impact for the entire life cycle were also discussed.

Figure 1. Duration distributions for household fittings.



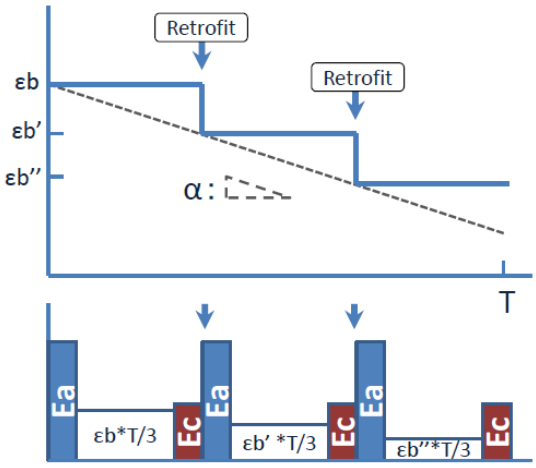
2. Calculation Method

The outline of life cycle CO_2 ($LCCO_2$) evaluation is shown in Figure 2. In general $LCCO_2$ inventory analysis, one cycle from production stage to use and disposal stages of product is taken into consideration. This technique cannot estimate the effect of retrofit. Therefore, this research evaluated through the life cycle of two or more products introduced by retrofit. The eco-efficiency of the fitting supplied to the market assumes that it was improved at the annual rate, α. The total environmental impact for a specified period, T, within repeating retrofits, was compared under various conditions. The total environmental impact is the sum of the production, use and abandonment stage loads. In the evaluation, the influence of each parameter on the annual rate average value of the total environmental impact within T period: $\varepsilon t_{(ave)}$ is discussed. The relation between $\varepsilon t_{(ave)}$ and each parameter is shown in Equation (1). Here, n is the number of retrofits within T period, Ea, and Ec are the environmental impacts of the production and disposal stages, respectively, and εb is the annual value of the impact of the use stage.

$$\varepsilon t_{(ave)} = \left\{ \sum_{i=0}^{n} \left[(Ea + Ec) + \varepsilon b \times \left(1 - \alpha \times i \times \frac{T}{n} \right) \times \frac{T}{n} \right] \right\} / T \quad (1)$$

A toilet bowl and a showerhead were chosen as the evaluation targets, and the parameters were extracted from previous papers. Since toilet bowls and showerheads were replaced within 30 years, as shown in Figure 1, the evaluation period, *T*, was set to 30 years. The environment impacts were expressed by the CO_2 emissions, and *Ea* and *Ec* were assumed not to change with each retrofit.

Figure 2. Outline of evaluation concept.



3. Results and Discussion

3.1 Determination of Parameters

In Japan, the $LCCO_2$ calculation rules are determined as Product Category Rules by the Japan Environmental Management Association for Industry, and the $LCCO_2$ data on different products are released with these calculations according to the rules [14]. The $LCCO_2$ data for toilet bowls have also been published [15]. The outline of a calculation model and the $LCCO_2$ data are shown in Table 1 and Figure 3, respectively [14,15]. In the calculation, 0.59 kg CO_2/m^3 was adopted as CO_2 emission factor of water, and the duration was set as 10 years. From these results, *Ea*, *εb*, and *Ec* were determined as shown in Table 2. *Ea* was expressed as a sum of three stages of raw material production, production and distribution. Based on the above calculation rules, the parameters of showerheads were also determined. It became apparent that the environmental impacts of the production and disposal stages for a toilet bowl were far larger than the impact of the use stage, as shown in (*Ea* + *Ec*)/*εb* in Table 2.

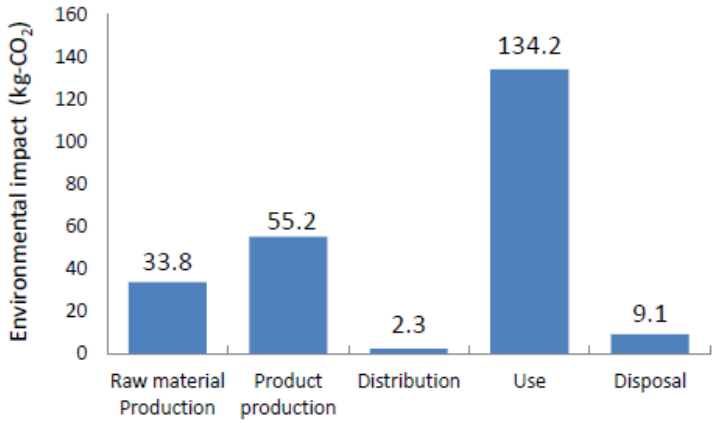
Table 1. Use stage calculation model for toilet bowls in homes.

Parameter	Male	Female
Number of eliminations	Defecation: 1/(person·day) Urination: 3/(person·day)	
Number of family members	2	2
Number of uses	365 days/year	

Table 2. Environmental impacts of toilet bowls and showerheads.

Item	*Ea* + *Ec* (kg CO_2)	*εb* (kg CO_2/year)	(*Ea* + *Ec*)/*εb*
Toilet bowl	100.5	13.4	7.5
Showerhead	0.7	238.9	0.002

Figure 3. The life cycle CO_2 ($LCCO_2$) data for toilet bowls.



Next, the eco-efficiency improvement rate, α, of each product was determined. For the toilet bowl, the amount of flush water was regarded as the environmental performance, and α was determined as an approximation of an annual performance improvement rate based on the transition data of the performance of the toilet bowl sold to each fiscal year. The amount of flush water was calculated according to Table 1. In the design of a toilet bowl, the amount of flush water is established as the quantity required to discharge the filth from the bowl and transport it more than 10 m in a sewage pipe. Those evaluation methods are specified as The Filth Discharge Performance Test [16] and The Transport Performance Test [17] in Japan. In Japan, although there are no legal regulations regarding water saving, the development of water-saving performance is progressing as part of market demand to reduce running costs.

The traditional toilet bowl design achieved fluidity due to the potential energy of the water in the tank positioned above the bowl. A reduction in the amount of flush water was achieved by lessening the fluid resistance of the trap parts, *etc.* As a result, although the amount of flush water was 16 L up until the start of the 1970s, a 13 L toilet bowl appeared in 1976, and since then, the reduction has been progressing continuously. In the newest water-saving toilet bowls, it has evolved into a new flushing system that causes a whirlpool using the pressure of tap water, instead of the traditional system using the potential energy of stored water [18]. The flushing system of a toilet bowl and the change in the amount of water used per family are shown in Figures 4 and 5, respectively, which show that α of a toilet bowl can be approximated as an annual rate improvement of 3%.

For the showerhead, the flow rate was adopted as the environmental performance in this evaluation. With respect to showerheads being installed in newly built houses, the recommended flow rate is prescribed in an act promoting energy saving in Japan. In response to the act, a measurement method for the flow rate for showers has been established by the Japan Valve Manufacturers' Association [19], with the aim of supplying showerheads that both meet users' satisfaction requirements and save water. The

measurement method used evaluates the amount of water saving under the optimum flow rate from which user satisfaction is obtained. The optimum flow rate is determined by sensory analysis, which measures the relationship between a user's degree of satisfaction and the flow rate. A monitor evaluator receives a shower stream on a breast as raising the flow rate gradually, and determines the five-step evaluation as shown in Figure 6.

In the act mentioned above, a shower flow rate of less than 8.5 L/min is recommended. Therefore, bubble-flow showers, which introduce air into the water stream to reduce the water flow rate, have been developed in Japan and in European countries in recent years. The newest shower structure and the transition of the flow rate are shown in Figures 7 and 8, respectively, which show that α of the shower was approximated at an annual rate improvement of 1%.

Figure 4. Toilet bowl flushing types.

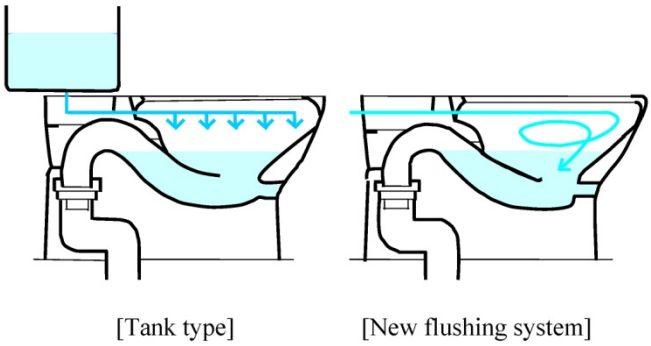


Figure 5. Eco-efficiency improvement rate *α* of toilet bowl.

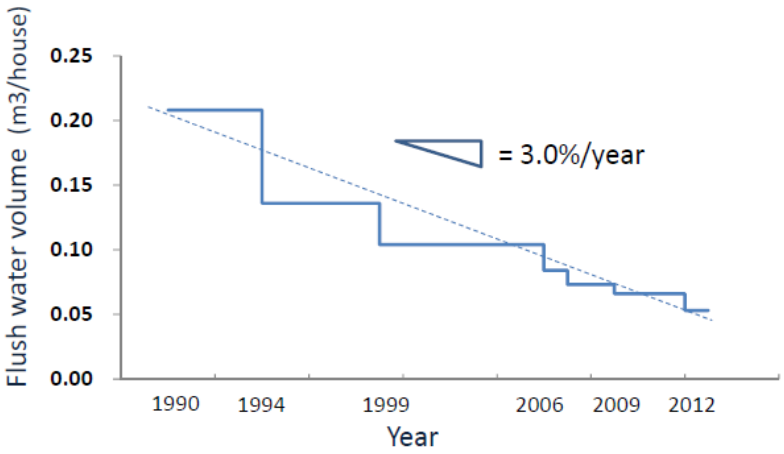


Figure 6. Graph of flow rate evaluation for shower.

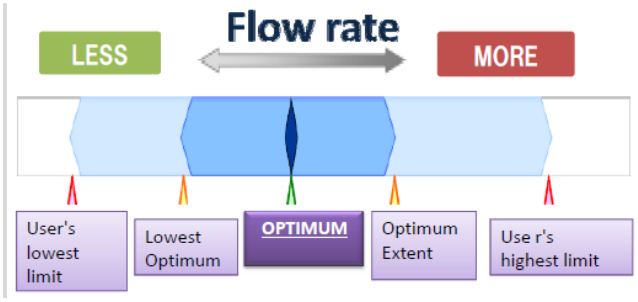


Figure 7. Outline of water-saving shower in Japan.

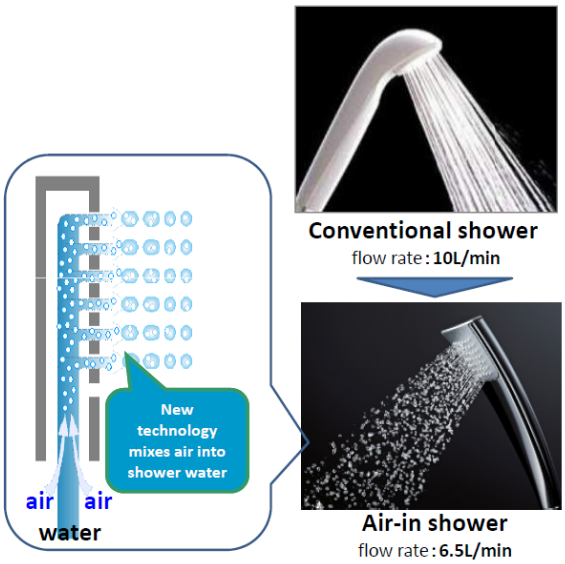
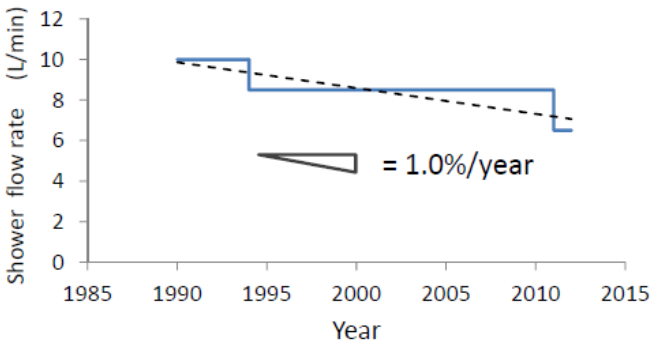


Figure 8. Eco-efficiency improvement rate, α, of showerhead.



3.2 Influence of Number of Retrofits on Total Environmental Impact

An example that evaluates the influence of the number retrofits, n, to total environmental impact, $\varepsilon t_{(ave)}$, is shown in Figure 9. The findings of this study indicate that there is an optimum retrofit frequency to minimize $\varepsilon t_{(ave)}$ for the product, whereby eco-efficiency is improved every year. This optimum retrofit frequency is decided by α and $(Ea + Eb)/\varepsilon b$.

As shown by the X symbol in Figure 10, the total impact, $\varepsilon t_{(ave)}$, for a toilet bowl was found not to increase for one retrofit in 30 years (duration period of 15 years).

Since the loads for the production and disposal stages of a shower were small as compared with the use stage, an early retrofit could reduce $\varepsilon t_{(ave)}$, as shown in Figure 11.

As shown in Figure 1, in the Japanese market, a shower and toilet bowl are replaced at about 13 and 20 years, respectively [9]. From the viewpoint of the environmental impact reduction as determined by this research, this is judged to be proper retrofit timing. Moreover, retrofits aiming at making an environmental contribution occur 2 years earlier than on average, as described in a previous paper [9]. The promotion of a retrofit by provision of a spread subsidy, *etc.*, can reduce not only the impact of use stage, εb, but the total impact, $\varepsilon t_{(ave)}$, in a shower.

Figure 9. Relationship between *εt* and *n*.

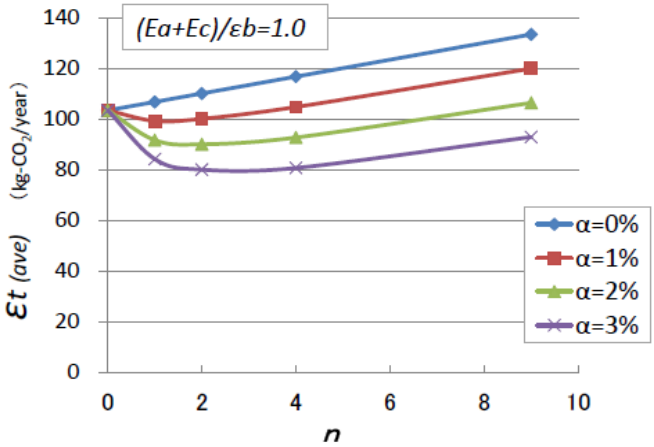


Figure 10. Environmental impacts of toilet bowls.

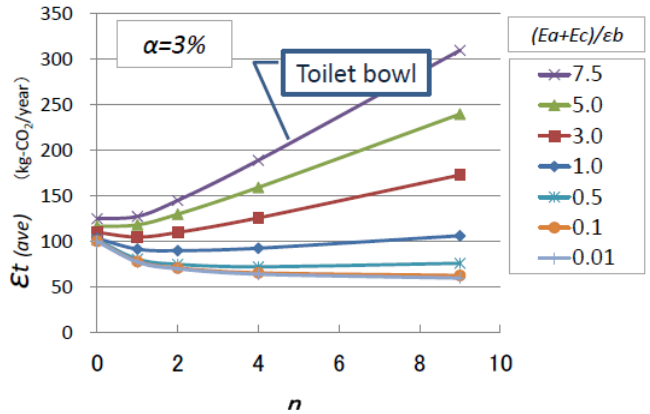
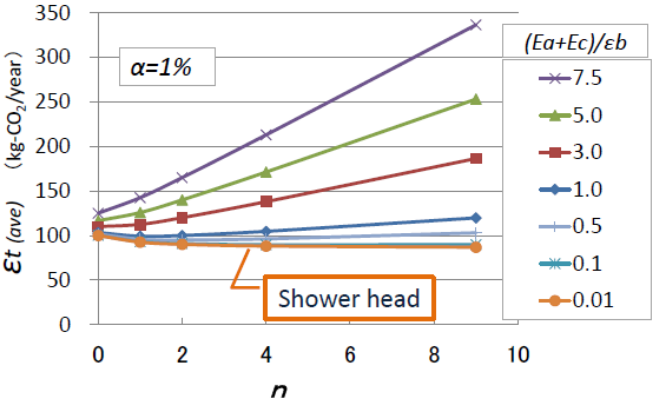


Figure 11. Environmental impacts of showerheads.



4. Conclusions

In recent years, studies associating water use and CO_2 emissions have been performed globally. In Japan, research related to the water-saving performance of bathroom fixtures such as toilets and showers that reduce CO_2 emissions has also progressed, and hence, Housing-Eco-Point subsidies have been introduced to promote the replacement of traditional toilets with water-saving ones. However, as for sanitation products that consume large amounts of energy in the production and disposal stages, there

has been a question as to whether the reduction in environmental impact obtained by retrofitting cancels the burden imposed by the impacts of the production and disposal stages. In the case of a retrofit at 20 years (average duration period of the present toilet bowl), it transpires that the environmental impact at the use stage can be reduced without raising the total impact. Moreover, even if a showerhead is retrofitted in just several years, it is shown that not only the impact at the use stage but the total impact offers a reduction.

In this study, various parameters were determined from data ranging from 1990 to the present. Within this period, thanks to the development of computer simulation technology, improvements in the eco-efficiencies of fittings have progressed every year, as fitting a linear approximation. However, the water-saving performance of the toilet bowl is nearing its limit, and no great reductions can be expected in the future. In order to predict all the environmental impact reductions resulting from future retrofits, a study on predicting α by index approximation will be needed.

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