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Hybrid LCC of Appliances with Different Energy Efficiency

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Abstract

Goal, Scope and Background. This paper is concerned with a life cycle assessment (LCA) and life cycle costing (LCC) by the use of the waste input-output (WIO) quantity- and price model of air conditioners with different energy efficiency at the use phase (high-end, low-end and average models) that were available in Japan as of winter 2002. The functional unit is an air conditioner of the 2.5kW type that is used for 10 years, and then subjected to an end-of-life (EoL) process that is consistent with the Japanese law on the recycling of appliances.

Methods. This is the first simultaneous application of the WIO methodology to an LCA and LCC over the entire life-cycle of a product including the use phase, and represents a methodological extension (in the sense of considering the use phase) and integration (in the sense of a simultaneous application) of previous studies by us (Kondo and Nakamura, Int J LCA 2004, Nakamura and Kondo, Ecol Econ 2006). The main body of data is provided by the WIO table for the year 2000, an update of the previous table for 1995 that was used in the above WIO studies. Compared with the WIO table for 1995 that consisted of only about 80 industry sectors, the current one consists of about 400 industry sectors, and includes air conditioner as a separate sector. The data on the purchase price and efficiency of air conditioners indicate wide variations: the cheapest one (the low-end model) costs half of the most expensive one (the high-end model), but its efficiency is about half of the latter.

Results and Discussion. When the cost in the use and EoL phases is included, the low-end model becomes the most expensive one, and the high-end model with the highest purchase cost the least expensive. This reversal of the relative cost levels is attributed to the difference in the efficiency in the use phase. A sensitivity analysis indicates that a reduction of the electricity price in the use phase by about 40% does not alter the significant superiority of the high-end model over the low-end model. In spite of the largest amount of input in the production phase, the high-end model performs the best in terms of both global warming potential (GWP) and landfill, while the low-end model performs the worst. The use phase generates the largest amount of waste for landfill across the three models, the largest component of which is flyash generated from coal firing power plants. A possible internalization of externality in the form of carbon tax was found to work in favor of the high-end model. The cost advantage of the high-end model, however, is sensitive to the rate of discounting of future costs: discounting at 15% diminishes its advantage over the low-end model.

Recommendation and Perspective. The results indicate the effectiveness of the pricing based on the life cycle cost for achieving sustainability, that is, for promoting the shift of the demand away from appliances with low environmental performance to the one with higher environmental performance. Acceptance by society of pricing based on life cycle costing would require, among other things, an economy-wide standardization of the LCC concept (in a manner analogous to ISO-LCA) that can be used complementary to ISO-LCA.

Keywords: Air conditioner; carbon tax; life cycle costing; waste input-output

Introduction

However excellent a product may be environmentally, it would not come into wide use unless it is also economically affordable. Without a wide use in the economy, its potential to reduce environmental load remains unexploited. For the purpose of evaluating environmental and economic sustainability of a product, a life cycle assessment (LCA) of the product needs to be accompanied by a complementary evaluation of its cost aspect [1]. The aspect of cost here should be the one that encompasses the cost associated with the whole life-cycle of a product, that is, the life cycle cost. The life cycle cost is in general not visible, because the market price of a product usually does not reflect the cost in the use and end-of-life (EoL) phases. It needs to be evaluated just as one needs an LCA to evaluate environmental impact of a product. The environmental life cycle costing (LCC) is a tool that is designed to meet this requirement [2].

Because of their complimentary use, it is desirable that the methodologies of LCC and LCA be based on the same theoretical framework and data set. The waste input-output (WIO) is a hybrid methodology of LCA that is capable of taking into account all the phases of life-cycle, production, use, and EoL [3]. Exclusion of the EoL phase used to be mentioned as a limitation of IOA for LCA ([4], p. 123) (while the conventional IOA does not cover the use phase as well, its incorporation is rather straightforward [5]). It, however, does not apply to the WIO because of its explicit consideration of the flow of waste and waste management activities including waste recycling. According to the classification by [6] and [7] of types of hybrid analysis, the WIO corresponds to integrated hybrid analysis, where the technology matrix of a product system in LCA (in particular the foreground processes that refer to waste management and recycling) is fully integrated with technical coefficients matrix of an economy (the background processes that refer to the traditional flow of goods and services) in IOA. We elsewhere have applied this methodology to an LCA of appliances with different EoL options, which range from landfilling, conventional recycling combined with simple shredding, to advanced recycling [8]. The cost aspect of this case study has been investigated by [9] based on a hybrid LCC tool termed the WIO price model, the economic counterpart of the WIO (quantity) model. While the WIO is able to take into account the use phase, in both the studies, the use phase was not considered, because they were mainly concerned with alternative EoL options: the appliances were assumed to have no efficiency difference in the use phase.

This paper is concerned with an LCA and LCC based on the WIO quantity- and price models of air conditioners (2.5 kW type) with different energy efficiency in the use phase which were available on the Japanese market as of winter 2002. This is thus the first simultaneous application of the WIO methodology to an LCA and LCC over the entire life-cycle of a product including the use phase. A recent example of a related study that deals with air conditioners is Yokota et al. [10], who applied a dynamic model that integrates LCA and the population balance model to the Japanese populations of air conditioners from 1990 to 2000. Their main concern was to evaluate environmental burdens of alternative dynamic replacement patterns of the populations over time. Because of this, intra-population differences in efficiency were not considered, while great attention was paid to consider inter population differences in efficiency and the type of refrigerant. In contrast, intra-population differences in efficiency are the main concern of this study. Furthermore, they were not concerned with economic aspects, but with environmental aspects only. From the methodological point of view, the two studies are also markedly different: their LCA is based on the conventional process based method, while ours is based on the WIO method.

This paper is structured as follows. Section 1 first sets up the problem of our concern, and then presents the hybrid WIO-LCA methodology that is tuned to dealing with that particular problem. Derivation of its LCC counterpart is dealt with in Section 2. This order of first presenting the LCA inventory part has been chosen, because "life cycle inventory (LCI), which is essentially a materials accounting application, is a prerequisite to cost accounting" [11]. Section 3 is devoted to the integrated application of both the LCA and LCC methodologies. The WIO table for the year 2000, an update of the previous table for 1995 that was used in the above WIO studies [8,9] provides the main body of data. While the WIO table for 1995 consisted of only about 80 industry sectors, the current one consists of about 400 industry sectors, which include air conditioner as a separate sector. Concluding remarks in Section 4 close the paper.

1 Hybrid LCA by Use of Waste IO

1.1 The foreground processes: Setting up the problem

We consider the life-cycle of a unit of home appliance, which is used for T years, discarded after that, and then subjected to an EoL process. Suppose that the production (denoted by the suffix P), use (denoted by the suffix U), and EoL processes (denoted by the suffix E) of the appliance are represented by the technical coefficients in **Table 1**. The input coefficient a_i^P refers to the amount of current input i, electricity or electric wire, for instance, that is used in producing one unit of appliance, the waste generation coefficient g_i^P refers to the amount of waste i, copper scraps or sludge, for instance, that is generated in the production process, and the emission coefficient e_i^P refers to the amount of emissions such as CO_2 or suspended particulate matter (SPM)

Table 1: Technical coefficients of the foreground processes related to a product (home appliance)

Phases	Production	Use	End of Life
Unit	One	One per year	One
Input of goods and services			
Input 1 (appliance)	0	0	0
Input 2	a_2^P	a_2^U	a_2^E
Input 3	a_3^P	a_3^U	a_3^E
⋮	⋮	⋮	⋮
Input n	a_n^P	a_n^U	a_n^E
Net waste generation (= gross generation minus recycling)			
Waste 1 (EoL appliance)	0	0	0
Waste 2	g_2^P	g_2^U	g_2^E
Waste 3	g_3^P	g_3^U	g_3^E
⋮	⋮	⋮	⋮
Waste k	g_k^P	g_k^U	g_k^E
Emission of effluents			
Emission 1	e_1^P	e_1^U	e_1^E
Emission 2	e_2^P	e_2^U	e_2^E
⋮	⋮	⋮	⋮
Emission l	e_l^P	e_l^U	e_l^E

that are emitted by the use of fossil fuels in the production process. A remark seems due on the meaning of 'net waste generation' in the definition of g_i^P's in Table 1. In the absence of any recycling of waste materials, g_i^P's refer to the amount of waste generated per unit of production, and are positive. If, however, there is recycling of waste in the sense that it is used as input in the process, then g_i^P refers to the total waste generated minus the amount recycled. g_i^P's can thus take a negative value when the amount of recycling exceeds that of generation. The columns referring to Use and EoL are defined in a similar way. The a_i^U in the Use column refers to the amount of input i, say electricity, that is consumed per year in the use phase. Similarly, g_i^U's refer to the net generation of waste in the use phase, such as used batteries, broken light bulbs, and discarded filters.

While these notations have been used elsewhere [3,5,8,9], for a better understanding to those who are familiar with the traditional LCA it seems worth linking them to the existing system of notations that are used in the traditional LCA as in [4]. First, the input coefficients a_i's correspond to the elements of the technology matrix A in the traditional LCA ([4], p. 17), except for that in the former an input is recorded with a positive value whereas in the traditional LCA it is recorded in a negative value and that in the former the output of appliance does not occur in the production process whereas it does in the traditional LCA. The input/output of appliance does not occur in the three processes in Table 1 because a_i's refer to current inputs only and the appliance is a final product that is used by the final demand only. This explains why all the elements of the first row that refer to the input of appliance (Input 1) are zero. As for the net waste generation coefficients g_i's, they correspond to the elements of the waste matrix W in the traditional LCA ([4], p. 61) except for that the positive entry of EoL appliance does not occur in the use process. All the elements of the row that refers to the EoL appliance (Waste 1) are zero because the waste coefficients g_i's refer to process wastes only that result from the current operation of relevant processes, and hence exclude EoL wastes. The issue of recording the EoL appliance will be discussed below in connection with **Table 2**. Finally, the emission coefficients e_i's correspond to the elements of the intervention matrix B in the traditional LCA ([4], p. 18).

Some remarks seem due on the EoL process that is supposed to consist of the collecting, disassembling, and shredding processes to which a discarded appliance is subject. In Table 1, a_i^E's give the EoL counterparts of a_i^P's and a_i^U's, and refer to the amount of inputs that are used in the EoL process for processing a unit of discarded appliance. The emissions per unit e_i^E's are also defined analogous to the e_i^P's and e_i^U's in the production and use phases. Characteristic to the EoL process is the waste generation per unit of treatment g_i^E's.

Table 2: Embedding the foreground processes within the framework of a WIO

	Production + Use [a]				End of Life				Final demand
	1	2	⋯	n	$n+1$	$n+2$	⋯	$n+m$	Household
Input of goods and services									
Input 1 (appliance)	0	0	⋯	0	0	0	⋯	0	1
Input 2	a_{21}^{P+U}	a_{22}^P	⋯	a_{2n}^P	a_{21}^E	a_{22}^E	⋯	a_{2m}^E	0
Input 3	a_{31}^{P+U}	a_{32}^P	⋯	a_{3n}^P	a_{31}^E	a_{32}^E	⋯	a_{3m}^E	0
⋮	⋮	⋮	⋱	⋮	⋮	⋮	⋱	⋮	⋮
Input n	a_{n1}^{P+U}	a_{n2}^P	⋯	a_{nn}^P	a_{n1}^E	a_{n2}^E	⋯	a_{nm}^E	0
Net waste generation (= gross generation minus recycling)									
Waste 1 (EoL appliance)	1	0	⋯	0	0	0	⋯	0	0
Waste 2	g_{21}^{P+U}	g_{22}^P	⋯	g_{2n}^P	g_{21}^E	g_{22}^E	⋯	g_{2m}^E	0
Waste 3	g_{31}^{P+U}	g_{32}^P	⋯	g_{3n}^P	g_{31}^E	g_{32}^E	⋯	g_{3m}^E	0
⋮	⋮	⋮	⋱	⋮	⋮	⋮	⋱	⋮	⋮
Waste k	g_{k1}^{P+U}	g_{k2}^P	⋯	g_{kn}^P	g_{k1}^E	g_{k2}^E	⋯	g_{km}^E	0
Emission of effluents									
Emission 1	e_{11}^{P+U}	e_{12}^P	⋯	e_{1n}^P	e_{11}^E	e_{12}^E	⋯	e_{1m}^E	0
Emission 2	e_{21}^{P+U}	e_{22}^P	⋯	e_{2n}^P	e_{21}^E	e_{22}^E	⋯	e_{2m}^E	0
⋮	⋮	⋮	⋱	⋮	⋮	⋮	⋱	⋮	⋮
Emission l	e_{l1}^{P+U}	e_{l2}^P	⋯	e_{ln}^P	e_{l1}^E	e_{l2}^E	⋯	e_{lm}^E	0

[a] The integration of the use phase with the production phase applies to sector 1 only

They refer to the amount of waste materials and residuals that are generated by disassembling and shredding of the EoL appliance. While the appliance is the output of the production process, g_i^E 's are the output of the EoL process, such as metal scraps, waste plastics, and shredding residues. The meaning of g_i^E 's is thus very different from that of g_i^P 's. In the absence of gaseous and liquid components, and of recycling of recovered materials within the EoL process, the mass balance condition between input and output implies the following equality:

$$\sum_{i=2}^{k} g_i^E = \text{the weight of discarded appliance (kg)}.$$

1.2 Integrating the manufacturing and use processes

In Table 1, there are certainly several inputs that are used in both the production and use phases, a typical example of which is electricity. Writing a^P and a^U for the $(n-1)$ column vectors of a_i^P 's and a_i^U 's, the amount of input i's used in both the production and use phases over T years, say a^{P+U}, can be given by

$$a^{P+U} = a^P + a^U \times T. \tag{1}$$

In an analogous manner, the net amount of waste and emissions in both the production and use phases can be given by:

$$g^{P+U} = g^P + g^U \times T, \quad \text{and} \quad e^{P+U} = e^P + e^U \times T. \tag{2}$$

Because the appliance is used by consumers, but not by producers, the inputs that are associated with the use phase are usually recorded in the final demand [5] ([12] considers an alternative approach where a matrix form is used to combine purchases of goods at the use phase to specific consumption activities such as 'washing' or 'car driving'). The way of recording the use phase makes computationally no difference in LCA. From the computational aspect of LCC, however, the above way of recording (in the production process) is more preferable because it allows a straightforward incorporation into the production cost of the cost at the use phase.

In the present case, it is assumed that the unit input of the use phase remains constant over T years. It may be the case, however, that the performance of the appliance deteriorates over the years, which results in the increase of some input, say electricity. This case can easily be dealt with by replacing the constants a^U's by ones that are time dependent, say $a^U(t)$. In that case, Eq. 1 can be replaced by

$$a^{P+U} = a^P + \sum_{t=1}^{T} a^U(t).$$

The application of a similar approach to g^{P+U} and e^{P+U} is straightforward.

1.3 Embedding the foreground processes into a WIO framework

For the purpose of a life cycle inventory analysis, the foreground processes need to be integrated with the background processes that refer to the production of all the inputs entering the foreground processes and waste management of all the waste items generated by the foreground processes. Because the background processes are also mutually interrelated through the flow of inputs (goods) and waste, this integration will easily extend over almost the entire economic system. Expanding the system boundary to the entire economy is practically impossible along the lines of an LCA based on process data alone. Here lies the great advantage of resorting to a hybrid method [13] (as pointed out by [4] and [7], however, at practical levels the theoretical advantage of hybrid analysis could be hampered by, among others, the coarseness of the industrial classification of available input-output (IO) tables).

Table 2 shows the result of embedding the foreground processes in Table 1 into a WIO framework representing all the processes (sectors) in the entire economy that consist of n goods-producing sectors and m waste management sectors. In Table 2, the integrated process of production and use of appliance, the technical coefficients of which are given by Eq. 1 and Eq. 2, occurs as the 1st sector, and its EoL process as the n+1st sector. In accordance with this, a second subscript is introduced to identify the column (sector/process) number: a_{21}^{P+U} thus refers to $a_2^P + a_2^U \times T$, and g_{21}^{P+U} refers to $g_2^P + g_2^U \times T$ in Table 1. In a similar fashion, the third column elements from the left refer to the technical coefficients of goods-producing sector (process) 2, and the second column elements from the right refer to those of m-th EoL process. Note that the embedded matrix of a's in 'Production + Use' is square $(n \times n)$, while it was not the case in Table 1.

Besides the occurrence of background processes, Table 2 differs from Table 1 in two respects. First, the column termed 'Final demand' occurs as the far right column, the elements of which are zero except for the first element, which refers to the purchase of a unit of appliance by the household. The term final demand represents a reference flow, a unit of appliance, and corresponds to that of the traditional LCA ([4], p. 14). Secondly, the generation of a unit of EoL appliance occurs in the column of the 1st sector that refers to the integrated production and use process of the appliance. Because the EoL appliance is generated by consumers, but not by producers, it may appear more legitimate to record the generation of the EoL appliance in the final demand column as [5,8] instead of the production column. From the computational aspect of LCA, however, it makes no difference whether the EoL appliance is recorded in the final demand or in the production process. From the computational aspect of an LCC, this way of recording (in the production process) is attractive because it allows a straightforward incorporation into the production cost of the EoL cost in addition to the use cost.

1.4 Life cycle inventory analysis

Let x be an $(n + m) \times 1$ vector of output (activity level of process), which corresponds to the scaling vector in the traditional LCA ([4], p. 16), and w be an $k \times 1$ vector that refers to the amount of net generation of k types of waste. Then, we can obtain from Table 2 the following set of equations for x and w:

$$x_1 = f_1 = 1, \tag{3}$$

$$x_i = a_{i1}^{P+U} x_1 + \sum_{j=2}^{n} a_{ij}^P x_j + a_{i1}^E x_{n+1} + \sum_{j=2}^{m} a_{ij}^E x_{n+j}, \quad i = 2, \ldots, n, \tag{4}$$

$$w_1 = g_{11}^{P+U} x_1 = x_1, \quad (5)$$

$$w_i = g_{i1}^{P+U} x_1 + \sum_{j=2}^{n} g_{ij}^{P} x_j + g_{i1}^{E} x_{n+1} + \sum_{j=2}^{m} g_{ij}^{E} x_{n+j}, \quad i = 2,\ldots,k, \quad (6)$$

where f_1 refers to the first element of the final demand. This system of equations is still not solvable, because the equations for x_j, $j = n + 1,...,n + m$, are missing. Following the methodology of WIO [3], the k Eqs. 5 and 6 that refer to wastes can be transformed into the m equations referring to the output of waste treatment sectors x_j, $j = n + 1,...,n + m$, by considering the mapping between waste types and its treatment. Recall that by assumption the EoL appliance is subjected to the n+1st sector, which implies from Eq. 5:

$$x_{n+1} = x_1 . \quad (7)$$

This is a special case of the mapping where there is a one-to-one correspondence between waste and its treatment. For the remaining $k - 1$ types of waste, however, it is necessary to consider a general case where this simple correspondence does not hold. The mapping for the general case can be represented by the allocation matrix S of order $(m - 1) \times (k - 1)$, the (i,j)-element of which, that is, s_{ij}, refers to the share of the j-th waste that is treated by the i-th waste treatment process [3]. Multiplication of Eq. 6 from the left by S then yields the $m - 1$ equations for x_j, $j = n + 2,...,n + m$:

$$x_{n+i} = \sum_{l=2}^{k} s_{il} g_{l1}^{P+U} x_1 + \sum_{j=2}^{n}\sum_{l=2}^{k} s_{il} g_{lj}^{P} x_j + \sum_{l=2}^{k} s_{il} g_{l1}^{E} x_{n+1} + \sum_{j=2}^{m}\sum_{l=2}^{k} s_{il} g_{lj}^{E} x_{n+j}, \quad i = 2,\ldots,m. \quad (8)$$

Note that Eq. 7 corresponds to the case where waste 1 is allocated to only the n+1st sector but to no others for its treatment.

Stacking Eqs. 3, 4, 7, and 8 together and using obvious matrix notations results in the following system of equations:

$$\begin{pmatrix} x_1 \\ \bar{x}^P \\ x_{n+1} \\ \bar{x}^E \end{pmatrix} = \begin{pmatrix} 0 & O & 0 & O \\ a_1^{P+U} & \bar{a}^P & a_1^E & \bar{a}^E \\ 1 & O & 0 & O \\ Sg_1^{P+U} & S\bar{g}^P & Sg_1^E & S\bar{g}^E \end{pmatrix} \begin{pmatrix} x_1 \\ \bar{x}^P \\ x_{n+1} \\ \bar{x}^E \end{pmatrix} + \begin{pmatrix} 1 \\ O \\ 0 \\ O \end{pmatrix}, \quad (9)$$

where O refers to a zero matrix of appropriate order, x^P refers to the $(n - 1)$-vector of x_i, $i = 2,...,n$, and x^E refers to the $(m - 1)$-vector of x_i, $i = n + 2,...,n + m$. Solving this system of equations for x, and multiplying them with the emission coefficients yields the emission of effluents associated with the life-cycle of a unit of appliance:

$$\begin{pmatrix} e_1^{P+U} & \bar{e}^P & e_1^E & \bar{e}^E \end{pmatrix} \left(I - \begin{pmatrix} 0 & O & 0 & O \\ a_1^{P+U} & \bar{a}^P & a_1^E & \bar{a}^E \\ 1 & O & 0 & O \\ Sg_1^{P+U} & S\bar{g}^P & Sg_1^E & S\bar{g}^E \end{pmatrix} \right)^{-1} \begin{pmatrix} 1 \\ O \\ 0 \\ O \end{pmatrix}, \quad (10)$$

where I refers to an identity matrix of appropriate order. In IOA, the inverse matrix in Eq. 10 is known as the Leontief inverse matrix. It is interesting that, at least formally, exactly the same form of equations occurs in the traditional LCA: Eq. 10 corresponds to $B\,A^{-1} f$ in [4].

Decomposition of the environmental load into each of the life cycle phases can be facilitated by modifying (10). For instance, the load associated with the manufacturing and use phases can be obtained by replacing 1 in the inverse matrix by 0. Additional replacement of a_1^{P+U} and g_1^{P+U} by a_1^P and g_1^P, respectively, then yields the load associated with the manufacturing phase only.

2 From the Hybrid LCA to a Hybrid LCC

After having presented the hybrid LCA methodology that is a prerequisite to LCC [11], it is now time turn to its LCC counterpart.

2.1 The components of life cycle cost

In contrast to LCA, there is no uniform understanding of the term life cycle costing nor is there a standardized methodological framework that is commonly used in business [14]. The notion of LCC that we use here is the environmental LCC that is being developed in the SETAC LCC Working Group within the framework of life cycle management (LCM) [2,15]. The life cycle cost then consists of the following components [1]:

$$LCC := R\,\&\,D + MAT + TRNS + MANF + USE + EL + TC \quad (11)$$

where $R\,\&\,D$, MAT, $TRNS$, $MANF$, USE, EL, and TC refer to the costs for research and development (R&D), materials, transport/logistics, manufacturing, use, end-of-life, and transaction. To the extent that they refer to current expenditures, $R\,\&\,D$, MAT, $TRNS$, $MANF$, and TC occur in the usual IO data. We saw above how USE and EL and can be included in the WIO framework. It follows that all the cost elements occurring in Eq. 11 have already been taken care of in the WIO framework. It is no wonder because 'life cycle inventory (LCI), which is essentially a materials accounting application, is a prerequisite to cost accounting' [11]. What remains to be done is to formulate a practical mathematical model to compute LCC under given conditions.

2.2 The computational structure of a hybrid LCC

We now turn to modeling of the LCC concept (11) by use of the WIO price model [9], a cost and price counterpart of the WIO (quantity) model. Consideration of the cost makes it necessary to distinguish the components of net waste generation, gross waste generation and gross waste input (recycling), because different costs or prices can apply to them. Writing $g_{kj}^{\oplus}$ for the gross generation of waste k in sector j per unit of output, and $g_{kj}^{\ominus}$ for the input (recycled use) of waste k in sector j per unit of output, we have (the suffixes P, U, E, and $P + U$ are omitted for simplicity):

$$g_{kj} = g_{kj}^{\oplus} - g_{kj}^{\ominus} \quad \text{for all } k, j. \quad (12)$$

It is important to note that intra-sectoral transactions of waste are netted out, which implies the exclusion of the case where $g_{kj}^{\oplus}$ and $g_{kj}^{\ominus}$ simultaneously take non-zero values.

A remark is due on the price of waste materials and waste treatment services. Of the waste items, metal scraps and waste paper are characterized by the presence of well-established national markets, the movement of which is closely correlated with that of the corresponding international market of virgin materials. (Our definition of waste is a broad one, and includes scraps that are usually traded with positive prices. This definition of waste is also used in [16,17].) It is then legitimate to treat the price of these waste items as exogenously given. For the remaining waste items, nationwide markets are almost nonexistent. In fact, it is frequently the case that their price takes a negative value even when they are recycled as input in the production process; a typical example is the injection of waste plastics into blast furnaces in steel mills. This type of recycling (with payment for acceptance) is in competition with conventional waste treatment. In the absence of detailed information on the price of these wastes, it can be approximated by the negative of (the average weighted by the amount of treatment of) the cost of competing waste treatment processes.

Following the methodology of WIO price model [9], the life cycle cost of a unit of appliance, p_1, can then be given by

$$p_1 = \sum_{i=2}^{n} p_i a_{i1}^{P+U} + \sum_{i=2}^{m} p_i^E \sum_{j=2}^{k} s_{ij}(1-r_j) g_{j1}^{P+U\oplus} + \sum_{i=2}^{k} p_i^w (g_{i1}^{P+U\ominus} - r_i g_{i1}^{P+U\oplus}) + v_1 + p_1^E, \tag{13}$$

where r_i refers to the recycling rate of waste i that is determined by Eq. 9, p_i^w to the price of waste material i, p_1^E to the EoL cost per unit of discarded appliance, p_j^E to the treatment cost per unit of waste in treatment sector j such that $j > 1$, and v_j to the ratio of value added (the unit cost of primary inputs). In Eq. 13, the first term on the right hand side refers to the cost for the input of goods and services, the second term to the cost for treatment of waste generated in the production and use phases, and the third term to the cost for the input of waste. Because $g_{i1}^{P+U\oplus}$ and $g_{i1}^{P+U\ominus}$ cannot take non-zero values at the same time, the sum of the second and the third terms for a given waste, say i, gives either the cost for treating that waste net of the revenue from its sale to other sectors as waste material (when $g_{i1}^{P+U\oplus} > 0$ and $g_{i1}^{P+U\ominus} = 0$), or the cost for the input as waste material of that waste generated in other sectors (when $g_{i1}^{P+U\ominus} > 0$ and $g_{i1}^{P+U\oplus} = 0$).

In a similar fashion, the unit cost for other goods-producing sectors and waste management sectors is respectively given by

$$p_j = \sum_{i=2}^{n} p_i a_{ij}^{P} + \sum_{i=2}^{m} p_i^E \sum_{o=2}^{k} s_{io}(1-r_o) g_{oj}^{P\oplus} + \sum_{i=2}^{k} p_i^w (g_{ij}^{P\ominus} - r_i g_{ij}^{P\oplus}) + v_j, \quad j = 2, \cdots, n, \tag{14}$$

$$p_j = \sum_{i=2}^{n} p_i a_{ij}^{P} + \sum_{i=2}^{m} p_i^E \sum_{o=2}^{k} s_{io}(1-r_o) g_{oj}^{P\oplus} + \sum_{i=2}^{k} p_i^w (g_{ij}^{P\ominus} - r_i g_{ij}^{P\oplus}) + v_j, \quad j = 2, \cdots, n, \tag{15}$$

Stacking Eq. 13, 14, and 15, we then obtain the following system of equations for prices:

$$\begin{aligned}(p_1 \;\; \bar{p} \;\; p_1^E \;\; \bar{p}^E) &= (p_1 \;\; \bar{p} \;\; p_1^E \;\; \bar{p}^E) \\ &\times \begin{pmatrix} 0 & O & 0 & O \\ a^{P+U} & \bar{a}^P & a_1^E & \bar{a}^E \\ 1 & O & 0 & O \\ S(I-D)g^{P+U\oplus} & S(I-D)\bar{g}^{P\oplus} & S(I-D)g_1^{E\oplus} & S(I-D)\bar{g}^{E\oplus} \end{pmatrix} \\ &+ p^w \left(g^{P+U\ominus} - Dg^{P+U\oplus} \;\; \bar{g}^{P\ominus} - D\bar{g}^{P\oplus} \;\; g_1^{E\ominus} - Dg_1^{E\oplus} \;\; \bar{g}^{E\ominus} - D\bar{g}^{E\oplus} \right) \\ &+ (v_1 \;\; \bar{v} \;\; v_1^E \;\; \bar{v}^E),\end{aligned} \tag{16}$$

where D is the diagonal matrix of r_i, $i = 2,...,k$, and the elements with a bar on top refer to those that exclude the appliance as in Section 1.4 above. Comparison of the coefficients matrix on the right-hand side with that of Eq. 10 reveals that the former collapses to the latter when $D = O$, that is, when there is no recycling of waste. Using a simplified notation, the above system of equations can be written:

$$p = pB + \omega + v, \tag{17}$$

the solution of which is given by

$$p = (\omega + v)(I - B)^{-1}. \tag{18}$$

The first element of p obtained this way gives the life cycle cost of the appliance.

3 Application and Results

3.1 Data and implementation

The above methodology is now applied to air conditioners of the 2.5 kW type that were available in the Japanese market in the winter of 2002. This particular type and year were chosen because of the ample availability of catalogue prices published by the manufacturers (in recent years, most manufacturers of home appliances have ceased publishing catalogue prices of their products). Electricity is the only significant input in the use phase of an air conditioner, which implies that it is the only non-zero element in a_1^U, and that its amount can be used as an efficiency measure at the use phase of the appliance. **Fig. 1** shows the scatter diagram of purchase price and the electricity consumption per year (3.6 months for cooling and 5.5 months for heating) for twenty models for which the purchase prices were available [18] (two outlier models were excluded from the diagram). The diagram indicates the presence of a clear negative correlation between the purchase price and the efficiency. While the cheapest model (132 thousand yen) costs about the half of the most expensive one (250 thousand yen), in terms of efficiency, the best performance is observed for the most expensive one (830 kWh per year), and the worst perform-

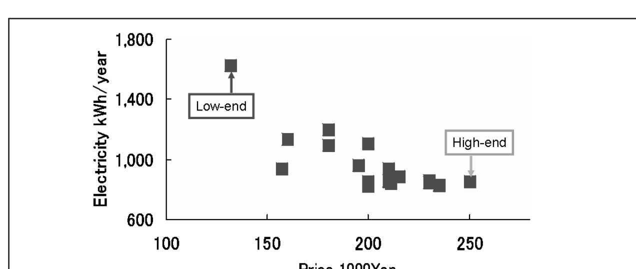

Fig. 1: Price and energy efficiency of air conditioners: 2.5kW models, 2002 winter, Japan. Source [18]

ance for the cheapest model (1680 kWh per year). Henceforth, the cheapest model with the lowest efficiency is called the low-end model, the most expensive model with the highest efficiency the high-end model, and the model with the average purchase price and the average efficiency the average model.

The Japanese WIO table for 2000, an updated version of the one for 1995 [19] based on the national IO table for 2000 [20], provides the basic data for the following analysis. The WIO table consists of 396 industry sectors, which include air conditioners, three basic treatment methods (shredding, incineration, and landfilling), and sixty-one waste types that cover municipal solid waste, commercial waste, and industrial waste. Shredding (including disassembling) is further disaggregated by waste types to be processed, and includes the EoL process of air conditioners, which was estimated following [8] in a way that is consistent with the technical requirements of the Japanese recycling law on EoL appliances. In particular, the recycling cost was made equal to the prevailing recycling fee of air conditioners by adjusting for the value-added components of the EoL process [9]. Incineration is also distinguished by major types of incinerator, and by the way of energy recovery and residue treatment.

Given the presence of enough demand for them, recovered waste materials are assumed to be recycled following the recycling scenario of [8] (p. 238): scraps of iron, copper, and aluminum are recycled for electric steel making, copper elongation, and aluminum rolling, respectively, while waste plastics are recycled in the iron and steel industry as a reductant in blast furnaces. The actual demand for recovered waste materials is determined by the level of output of their users, which is, in turn, induced by the given functional unit, as in Eq. 9. In the absence of a level of demand that is large enough to absorb all the recovered waste materials, some portions of them have to be subjected to waste management, such as landfilling.

While basic data on the production process of air conditioners come from the national IO table, some modifications are necessary to accommodate for the presence of different types of models (high-end, average, and low-end models). Recall that in the WIO price model the price of a product is set equal to its unit cost (see Eq. 13). Because the price of a given input or output is assumed to be the same across its users, the difference in purchase prices has to be attributed to the difference in inputs. High-end and low-end models may differ in their material composition. Due to the lack of detailed data on material composition and weight for different models, it was not possible to attribute the price difference to any difference in material inputs. Furthermore, comparison of a small number (about nine) of newer models [21] does not indicate any significant difference among models of different efficiency in terms of material composition and weight. The material composition and weight (44 kg, [22]) were hence assumed to be the same for all the models. This applies to the type of refrigerant as well: all the models are assumed to use the same amount of hydrofluorocarbon (HFC).

The actual modification of the input coefficients to accommodate for the price difference proceeded as follows. First, all the elements of the column of input and waste generation coefficients (of the air conditioner producing sector) were multiplied by the price of the average model to convert their value base from one million yen to a unit of the average model (in the Japanese IO table, a_{ij} refers to the input of i per one million yen of j). The column sum of the monetary inputs including value-added and the expenditure for net waste treatment (excluding the EoL cost of the appliance) then gives the purchase price of the average model. The coefficients for the high-end and low-end models were obtained by adjusting non-material inputs such as R&D, services, and energy. The price difference between the high-end and average models was attributed to the difference in the amount of R&D input. This simple procedure was not applicable to obtain a set of input coefficients for the low-end model, because the price difference was larger than the amount of R&D for the average model. For the low-end model, a proportional reduction of other non-material inputs was thus necessary, in addition to setting the R&D equal to zero.

Primary factors in the present context consist of labour, capital, imported intermediate inputs, and land for landfilling. The matrix of input coefficients a refers to domestic inputs only and does not include imports. The rent for landfill area per ton of waste was obtained following [23]. The price of iron scraps, nonferrous metal scraps (copper and aluminum), and waste paper were taken from the supplementary information of the Japanese IO table on physical flow of selected materials.

The emission of global warming potential (GWP, GWP_{100} in CO_2-equivalent) that originates from the combustion of fossil fuels and limestone, and the amount of landfill are used as a measure of environmental burdens.

As for the use phase, the appliance is assumed to be used for 10 years without any deterioration in its efficiency, that is, Eq. 1 applies with $T = 10$ with electricity the only non-zero element of a^U. The functional unit in our analysis is thus an air conditioner of 2.5 kW type that is used over 10 years.

3.2 Results and Discussion

The results of LCA and LCC are summarized in **Fig. 2**. The high-end model performs the best in terms of both GWP and landfill, while the low-end model performs the worst. As for life cycle costs, the high-end model turns out superior to (lower than) the low-end model, and is not inferior to (higher than) the average model. While the low-end model

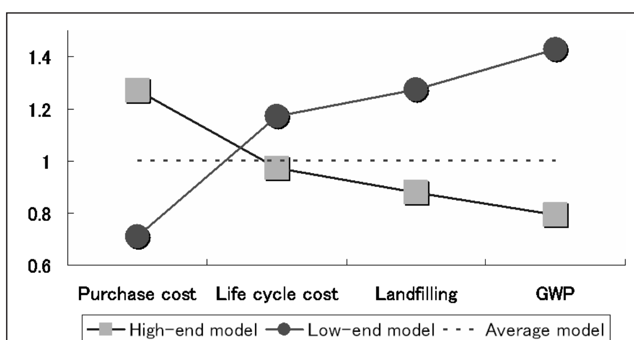

Fig. 2: Cost and environmental load of different air conditioners types: relative values with the levels of cost, landfilling, and GWP (GWP_{100} in CO_2 eq) set unity for the average model (discount rate=0)

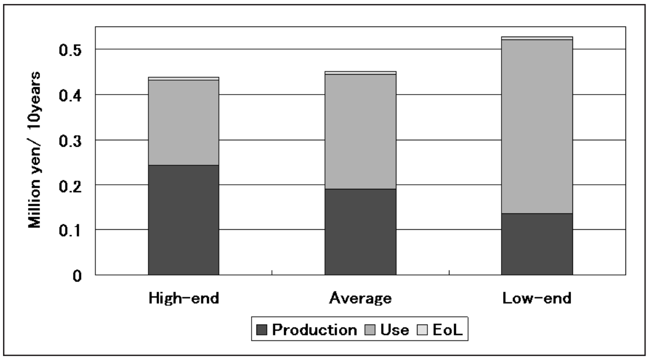

Fig. 3: Costs of air-conditioners in different phases of the life-cycle (production, use, and end of life). Discount rate=0%

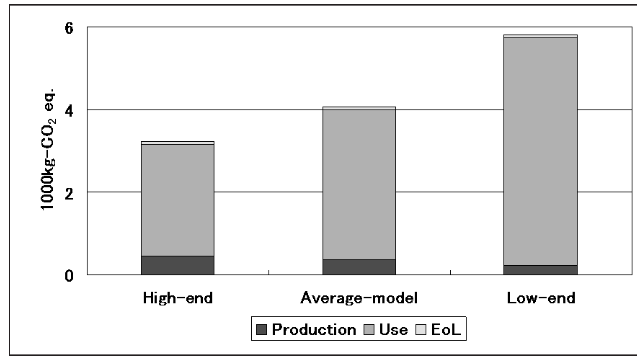

Fig. 4: GWP_{100} in CO_2 eq of air-conditioners in different phases of the life-cycle (production, use, and end of life)

has the lowest purchase price, inclusion of the cost in the use and EoL phases makes it the most expensive one. The difference in the efficiency in the use phase is responsible for this reversal of the relative cost levels (**Fig. 3**). A sensitivity analysis was conducted to see the effects on the relative cost levels of a change in the price of electricity in the use phase. Reducing the price of electricity per kWh in the use phase from 23 yen (this is the standard level that applies to the Japanese household [18]) to the national average (including agricultural, industrial, and commercial use) of 15 yen makes the life cycle cost of the high-end model slightly higher than the average model, but keeps the significant superiority of the high-end model over the low-end model unaltered.

By assumption, the high-end model uses the largest amount of (non-material) input, while the low-end model uses the smallest amount of input. This implies that the environmental burden in the production phase will be the largest for the high-end model, while it is the lowest for the low-end model. As far as the EoL phase is concerned, there is no difference in the level of environmental burden among them, because, by assumption, they have the same material composition, and are subjected to the same EoL process. The results in Fig. 2 then suggest that the burdens associated with the use phase must be large enough to more than offset those in the production phase.

Figs. 4 and **5** show that this is indeed the case for both GWP and the use of landfill.[1] The share of the use phase in GWP ranges from 84% for the high-end model to 95% for the low-end model, with that of the average model in between. This is followed by the production phase, the share of which is 14% for the high-end model and 4% for the low-end model. The share of the EoL phase remains at an almost negligible level of around 1 to 2%.

[1] In the literature on waste management, it is usual to measure the amount of landfill consumption by weight, see [16,24].

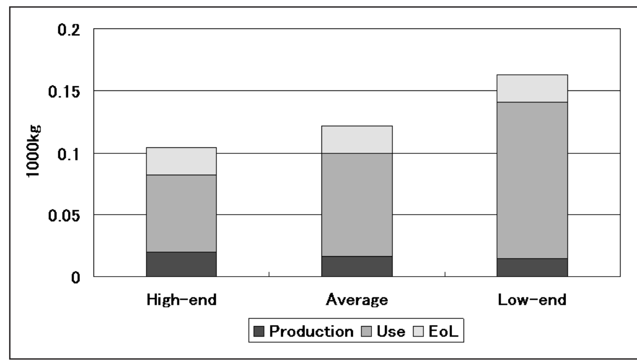

Fig. 5: Landfill consumption of air-conditioners in different phases of the life-cycle (production, use, and end of life)

The negligibly small share of the EoL phase in GWP appears inconsistent with a recent LCA study on Japanese air conditioners by Yokota at al. [10], where the share of the EoL phase amounts to about 17%, and exceeds that of the production phase of 3%. This difference is attributable to the use of different assumptions on the recovery of refrigerant in the EoL phase. In the present study, a 100% recovery of the refrigerant is assumed, because the recovery of refrigerant is mandatory under the Japanese law on the recycling of appliances. On the other hand, [10] assumes a 100% release into the atmosphere, which could have been the case prior to the enforcement of the law in 2001. However, **Table 3** shows that the use of different assumptions on the recovery of refrigerant does not alter the dominant importance of the use phase in GWP: the share of the use phase (50%) exceeds that of the EoL phase (40%) even for the case of high-end model with no recovery of refrigerant.

Table 3: Effects of refrigerant recovery on the share of use and end of life (EoL) phases in the generation of GWP

Rate of recovery	Use			End of Life		
	High-end	Average	Low-end	High-end	Average	Low-end
0.0	0.504	0.583	0.692	0.400	0.346	0.270
0.2	0.554	0.633	0.737	0.340	0.290	0.222
0.6	0.667	0.741	0.829	0.205	0.170	0.125
0.8	0.743	0.809	0.885	0.114	0.093	0.067

The figures show the share of Use and EoL phases in the total generation of GWP (GWP_{100} in CO_2 eq) in the life-cycle of air conditioners under alternative recovery rate of refrigerant. Each air conditioner is assumed to contain 1.2 kg of HFC R410A [10]

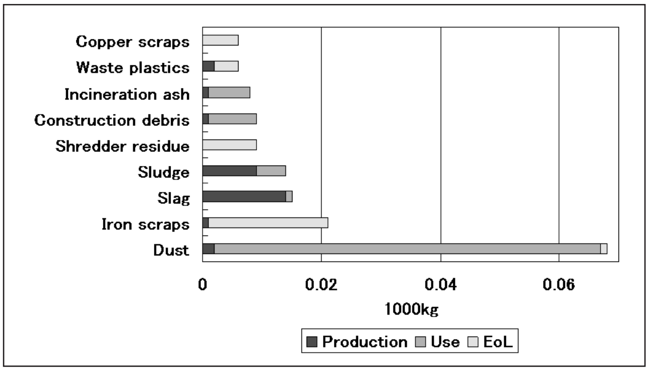

Fig. 6: Waste generation (net of recycling) of air-conditioners (average model) in different phases of the life-cylce (production, use, and end of life)

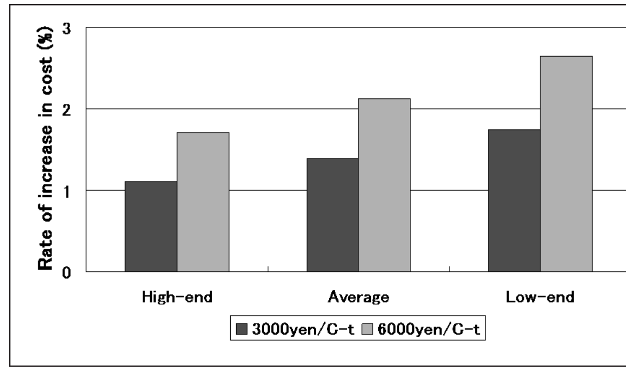

Fig. 7: Effects of Carbon taxes on the life cycle cost (discount rate=0%): C-t refers to carbon ton

The use phase was found to generate the largest amount of waste for landfill across the three models (see Fig. 5). Decomposition by the waste types and the life cycle phases (**Fig. 6**) indicates that the quantity and types of waste differ among the three phases. The production phase mostly generates slag and sludge, the use phase mostly generates dust (flyash), and the EoL mostly generates metal scraps, shredder residues (of the EoL appliance), and waste plastics. The largest share of landfill requirement (42%) comes from the disposal of flyash that is generated from coal firing electric power plants. In Japan, 18% of electricity comes from coal firing plants [25], and a coal firing power plant is known to generate 0.27 t of flyash per year per 1 kW [26].

According to the definition by [15], an environmental LCC should account for only internal and internalized costs except for those externalities "that are shown, based on preliminary or prior analyses, to introduce significant (potential) costs in the future due to internalization via regulatory measures (e.g., anticipated CO_2 taxes, renewable energy subsidies)". As an example of the internalization of this type of externality, we now consider the case where a carbon tax of t_1 per unit of carbon on fuel consumption is introduced. This example has been chosen because of the continuing discussion in Japan on the possible introduction of a carbon tax [27], and of the ease of implementation in the present study compared to, say, renewable energy subsidies. While there surely are other future cost drivers, they are not considered here for the sake of simplicity. Our primary intention is to illustrate how to incorporate such future cost items in the framework proposed here. Write ε_1 for the row of coefficients that refer to the emission of GWP in carbon equivalent. The vector of 'effective' rates of carbon tax, τ, is then given by multiplying each element of ε_1 by t_1. The change in the life cycle cost of appliance that results from the introduction of a carbon tax is then given by the first element of Δp:

$$\Delta p = (\omega + v + \tau)(I - B)^{-1} - (\omega + v)(I - B)^{-1} = \tau(I - B)^{-1}. \qquad (19)$$

Fig. 7 shows the effects on the life cycle cost of introducing a carbon tax on the consumption of fossil fuels. While the cost increases for each model, the rate of increase is the smallest for the high-end model and is the largest for the low-end model. The introduction of a carbon tax thus works in favor of the high-end models, provided the level of demand remains unchanged.

Discounting is a central element in all cost measures where cost is modeled as a time series. The present definition of LCC (11), however, deals with steady state costs, and does not make any discounting of future costs (this is in parallel to the current practice of LCA where there is no discounting of future environmental burdens). The sensitivity of LCC to the use of alternative discount rates is now considered. Write r for the rate of discounting, P for the cost of production, $U(t)$ for the use cost at year t, and E for the EoL cost. An LCC that discounts the stream of future costs over T years from the time of production can then be given by

$$\text{Discounted LCC} = P + \sum_{t=1}^{T} U(t)/(1+r)^t + E/(1+r)^T. \qquad (20)$$

The results in **Fig. 8** indicate that the cost advantage of the high-end model over the models with lower environmental performance is sensitive to the rate of discount. The cost advantage of the high-end model over the average model disappears at a discount rate of 5%. The high-end model becomes more expensive than the average model at a discount rate of 10%, and more expensive than the low-end model at 15%.

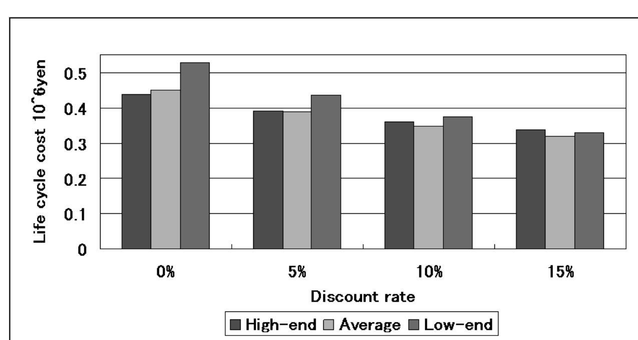

Fig. 8: Effects of discounting on the life cycle cost

4 Conclusion

A hybrid methodology of environmental LCC has been presented that is based on the WIO. Its applicability has been illustrated by a case study of air conditioners with different energy efficiency: the high-end model with the highest purchase price and energy efficiency, the average model, and the low-end model with the lowest purchase price and energy efficiency. The results indicate that in the absence of discounting (or discounting at a rate well below 5%) the high-end model turns out to be the one with the lowest life cycle cost, and the low-end model the one with the highest life cycle cost. In terms of environmental burdens represented by GWP and the use of landfill, the high-end model was found to perform the best, and the low-end model the worst.

It follows that, as far as this case study is concerned, the pricing based on the life cycle cost with a moderate rate of discounting can be an effective way for achieving sustainability, that is, for promoting the shift of demand away from appliances with low environmental performance to the one with higher performance. Acceptance by society of pricing based on LCC would require, among other things, an economy-wide standardization of the LCC concept (in a manner analogous to ISO-LCA) that can be used complementary to ISO-LCA.

In this study, pricing based on LCC was introduced for only one product. When the LCC-based pricing/costing is introduced into all the products in the economy, this would result in the emergence of an economy based on life cycle costing and pricing, which would represent a substantial departure from the current one where pricing is based on production costs alone. Investigation of the environmental and economic performance of this new LCC-based economy gives a challenging direction for future research.

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