LIFE CYCLE ASSESSMENT: A TOOL FOR EVALUATING AND COMPARING DIFFERENT TREATMENT OPTIONS FOR PLASTIC WASTES FROM OLD TELEVISION SETS

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ABSTRACT

In the present work, energy recovery and mechanical recycling, two treatment options for plastic wastes from discarded television sets, have been assessed and compared in the context of the life cycle assessment methodology (LCA). The environmental impact of each option was assessed by calculating the depletion of abiotic resources (ADP) and the global warming potential (GWP). Then, the indicators were compared, and the option with the smaller environmental impact was selected. The main finding of this study was that mechanical recycling of plastics is a more attractive treatment option in environmental terms than incineration for energy recovery.

Keywords: Life cycle assessment (LCA), Plastic wastes, Mechanical recycling, Energy recovery, Separation

1 INTRODUCTION

At some point, all appliances, including television sets (TVs), require some form of end-of-life management. Thus, the question is not "if" we will manage these appliances, but "when" and "how" to reuse, recycle, or properly dispose of them.

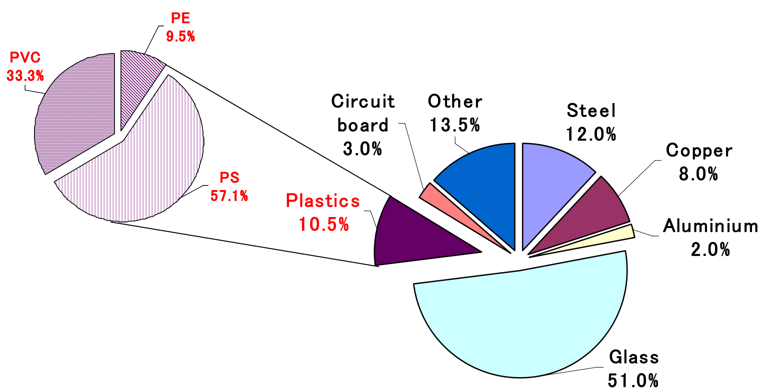

Figure 1. Materials composition of a TV set (wt%).

Figure 1 shows the composition of a TV set (Murakami, 2001) and the production in 2003 (Japan Almanac, 2005). It can be seen that glass is the main component (51 wt%), followed by steel (12 wt%), copper (8 wt%), aluminium

(2 wt%), and circuit boards (3 wt%) with electric components. In addition, there are also three types of plastics (10.5 wt%) from the TV cabinet, namely polystyrene (PS), polyvinyl chloride (PVC), and polyethylene (PE).

Generally speaking, good progress has been made in the recycling of discarded TV sets. The panel glass and funnel glass are recycled to make new cathode ray tubes. The steel and other metals are also recycled to make other new products. The plastic materials, on the other hand, are generally incinerated.

Several treatment options are considered when dealing with plastic wastes. At present, there are three main alternatives in addition to landfilling:

(1) *energy recovery* (also know as thermal recycling), i.e. direct incineration of plastic wastes for energy recovery,

(2) *mechanical recycling* (also known as material recycling), i.e. the method by which plastic wastes are recycled into new resources without affecting the basic structure of the material, and

(3) *feedstock recycling* (also know as chemical recycling), i.e. the technique that breaks down polymers into their constituent monomers, which in turn can be used again in refineries or petrochemical and chemical production.

In the present work, the energy recovery (1) and the mechanical recycling (2) of the plastic wastes from discarded TV sets are assessed and compared in the context of the life cycle assessment methodology (LCA).

2 LCA METHODOLOGY

Life cycle assessment (LCA) is a method for evaluating the environmental performance of a product or process, starting from raw material extraction, through manufacture and final disposal (Fig. 2) (U.S. E.P.A., 1993; ISO 14040, 1997; Curran, 1996).

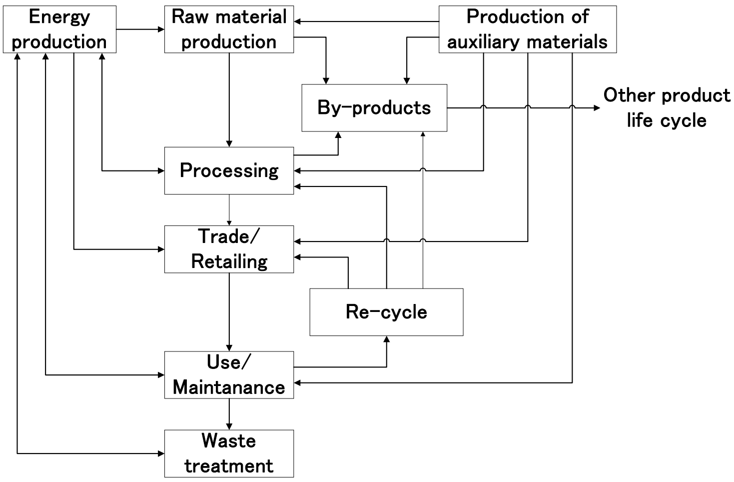

Figure 2. Life-cycle of a product, (ISO 14040, 1997; Curran, 1996).

LCA is generally carried out in four steps:

(1) *goal definition and scope*: (a) defining and describing the subject of the study, (b) determining the so-called "*functional unit*" f_u , i.e. the unit of comparison that assures that the options to be compared provide an equivalent level of function or service, (c) specifying the processes required in the manufacture, use, and eventual disposal of the products, (d) developing a flow diagram of the processes

to be evaluated, and (e) identify the boundaries and environmental effects to be reviewed for the assessment;

(2) *inventory analysis*: identifying and quantifying energy, materials usage, and environmental releases (atmospheric emission, waterborne emissions, etc.) for the entire life-cycle;

(3) *impact assessment*: assessing the human and ecological effects of energy, material usage, and the environmental releases identified in the inventory analysis;

(4) *interpretation:* evaluating the results of the inventory analysis and assessing the impact of each option under investigation in order to select the preferred one.

3 LCA OF TREATMENT OPTIONS FOR PLASTIC WASTES FROM THE DISCARDED TV SETS

3.1 Goal Definition and Scope

The first important step in carrying out the LCA was goal definition. In this work, two treatment options for plastic wastes generated from the efforts to recycle "old" TV sets have been considered:

Option 1: incineration of plastic wastes for energy recovery (electricity production)

Option 2: separation of plastic wastes for mechanical recycling.

To quantify the environmental impact associated with each recycling option, the functional unit was defined as "10 years use of color TV sets", i.e. f_u = 10 years. It is assumed that each TV set (screen: 25 inches; weight: 30 kg) contains 1.8 kg of PS, 1.05 kg of PVC and 0.30 kg of PE. Moreover, the number of discarded TV sets was considered to be 1.2 million sets per year, a number similar to that of the production of color TV sets in Japan in 2002 (Japan Almanac, 2005).

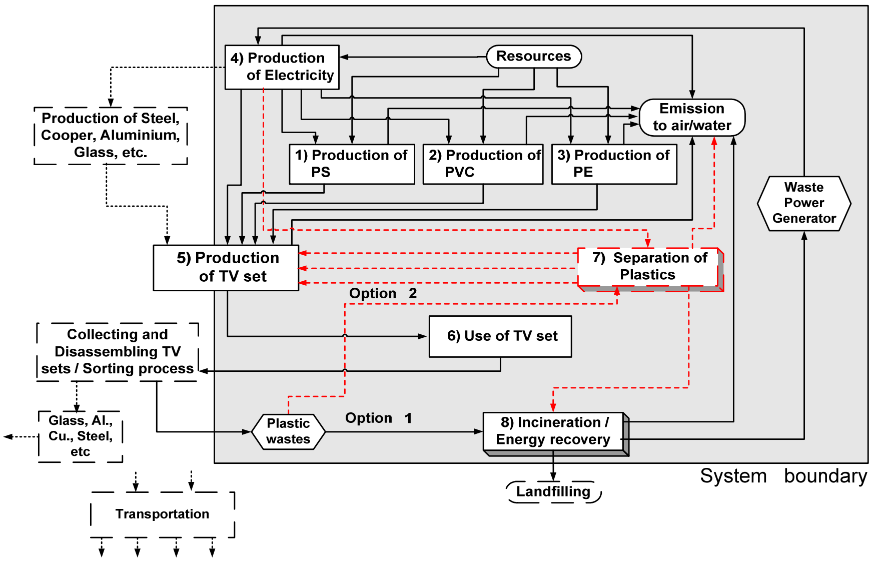

Figure 3. A simplified life-cycle of plastics for TV sets, indicating the system boundary.

A simplified life-cycle of plastics for production of color TV sets, indicating the system boundary and describing the relation between processes involved, is shown in Fig. 3. A look at Fig. 3 shows that the life-cycle of plastics starts with the extraction of resources (crude oil, coal, etc) needed for production of electricity and the production of PS, PVC, and PE. Then, the plastics (PS, PVC, and PE) are used as raw materials in the manufacturing process for color TV sets. After being discarded, the "old" TV sets are collected. It is assumed that the collection rate of the discarded TV sets is 100 %. The discarded TV sets are then dismantled, and their parts are sorted for recycling purposes. The sorting process results in the production of a mixed plastic product. It is also assumed that the sorting process is able to recovery 100 % of plastics being used in TV set production. Finally, there are only two possible treatment options for plastic wastes: (1) direct incineration for electricity production (energy recovery) or (2) separation of plastics according to their types for reuse in production of TV sets (mechanical recycling).

It is important to note that (a) processes for production of steel, copper, and aluminum, (b) the process for production of TV sets, as well as (c) the process for collecting and dismantling TV sets followed by sorting their parts according to the type of materials have not been included in the following inventory analysis, as these processes have the same influence on the life-cycle of plastics, regardless of the treatment option under investigation. A second important simplification is that the landfilling of the incinerator ash was excluded from the analysis because of a lack of data. Moreover, the last important simplification was that transportation was also excluded from the inventory analysis, assuming that the incinerator together with the waste power generated and/or the facility for separation of plastics are located in the vicinity of the collection point for "old" TV sets, which on the other hand is located in the same area with the facility for the production of color TVs.

Table 1. Manufacturing process of 1 kg PS (JEMAI On-line Database, 2005)

Category	Substance/Commodity	Amount
Economic Output	PS, (kg)	1
Economic inflow	Energy, (kcal)	4,567.1
	Electric power, kWh	0.133
	Naphtha, (kg)	0.962
	LPG, (kg)	0.014
	NGL, (kg)	0.025
	Oxygen gas, (kg)	0.012
Atmospheric emissions	CO_2 (g)	1387
	CH_4, (g)	0.031
	N_2O, (g)	0.0002
	NO_x, (g)	1.24
	SO_x, (g)	0.262
	Dust, (g)	0.0349
	HCl, (g)	0.0006
Waterborne emissions	Chemical oxygen demand, COD, (mg)	64.8
	T-P, (mg)	4.2
	T-Ni, (mg)	119
	Phenol, (mg)	0.1

3.2 Inventory Analysis

Inventory analysis, known as life cycle inventory (LCI), is the second phase in LCA. It consists of quantifying energy and raw material requirements, atmospheric emissions, waterborne emissions, solid wastes, and other releases for the entire life cycle of the plastics for color TV sets. Steps of LCI are as follows: (a) collect data and (b) create a computer model to evaluate the environmental loads related to each option under investigation.

Table 2. Manufacturing process of 1 kg PVC (JEMAI On-line Database, 2005)

Category	Substance/Commodity	Amount
Economic Output	PVC, (kg)	1
Economic inflow	Energy, (kcal)	4,937.9
	Electric power, kWh	0.29
	Naphtha, (kg)	0.435
	LPG, (kg)	0.009
	NGL, (kg)	0.016
	Oxygen gas, (kg)	0.124
Atmospheric emissions	CO_2 (g)	1,105
	N_2O, (g)	0.0002
	NO_x, (g)	1.01
	SO_x, (g)	0.313
	Dust, (g)	0.0296
	HCl, (g)	0.00082
	CO (g)	0.00624
Waterborne emissions	Chemical oxygen demand, COD, (mg)	268
	T-P, (mg)	7.7
	T-Ni, (mg)	152
	Phenol, (mg)	1.43

Table 3. Manufacturing process of 1 kg PE, (JEMAI On-line Database, 2005)

Category	Substance/Commodity	Amount
Economic Output	PE, (kg)	1
Economic inflow	Energy, (kcal)	3,540.8
	Electric power, kWh	0.08
	Naphtha, (kg)	0.959
	LPG, (kg)	0.02
	NGL, (kg)	0.035
Atmospheric emissions	CO_2 (g)	980.35
	CH_4, (g)	5
	N_2O, (g)	0.2
	NO_x, (g)	0.942
	SO_x, (g)	0.217
	Dust, (g)	21
	HCl, (g)	0.4
Waterborne emissions	Chemical oxygen demand, COD, (mg)	34
	T-P, (mg)	3
	T-Ni, (mg)	94
	Phenol, (mg)	0.1

The diagram shown in Fig. 3 provides the road map for data to be collected. The data on “manufacturing process of PS,” “manufacturing process of PVC,” “manufacturing process of PE,” “production of electricity,” and “manufacturing process of a TV set” were obtained from the LCA database of the Japan Environmental

Management Association for Industry (JEMAI) (JEMAI On-line Database, 2005). The initial magnitudes of the flows entering or exiting these unit processes are given in Tables 1 - 5.

Table 4. Production of 1 kWh electricity (JEMAI On-line Database, 2005)

Category	Substance/Commodity	Amount
Economic Output	Electricity, (kWh)	1
Economic inflow	LPG (kg)	0.00172
	Coal (kg)	0.05721
	Natural gas (kg)	0.0007025
	Petroleum (L)	0.01399
	Crude oil (L)	0.01239
	LNG (kg)	0.0491
Atmospheric emissions	CO_2 (g)	353
	HCF (g)	0.000013
	N_2O (g)	0.0021
	SF_6 (g)	0.000044
	NO_x (g)	0.18
	SO_x (g)	0.14
	Dust (g)	0.0074
Waterborne emissions	Chemical oxygen demand, COD, (mg)	0.15

Table 5. Manufacturing process of a TV set (weight: 30 kg; screen: 25 inch) (Murakami, 2001; JEMAI On-line Database, 2005). (*Note*: the economic inflows of steel, copper, aluminum, etc. have been excluded.)

Category	Substance/Commodity	Amount
Economic output	TV set, (No.)	1
Economic inflow	PS, (kg)	1.80
	PVC, (kg)	1.05
	PE, (kg)	0.30
	Electricity, (kWh)	9.4
Atmospheric emissions	CO_2 (g)	10,830
	NO_x (g)	8.49
	SO_x (g)	32.54

Table 6. Calorific value of plastics, (option 1), (PWMI, 2004)

Type of plastic	Calorific value, (kcal/kg)
PS	9,604
PVC	4,300
PE	11,140

Table 7. Electricity requirement for separation of plastics (option 2): system inputs

Unit Process	Electricity, (kWh/kg)
Triboelectrostatic separation	0.04
Air tabling	0.66
Size reduction	0.02
Sieving	0.02

With regard to the incineration of plastics for energy recovery (option 1), the energy generated from the incineration of plastics has been calculated based on their calorific values (Table 6). Power generating efficiency from the incineration of plastics is considered to be 15% (PWMI, 2004). Furthermore, the emission of CO_2 gas during the incineration of plastics is considered to be 2.55 kg CO_2 / kg (MEJ, 2006).

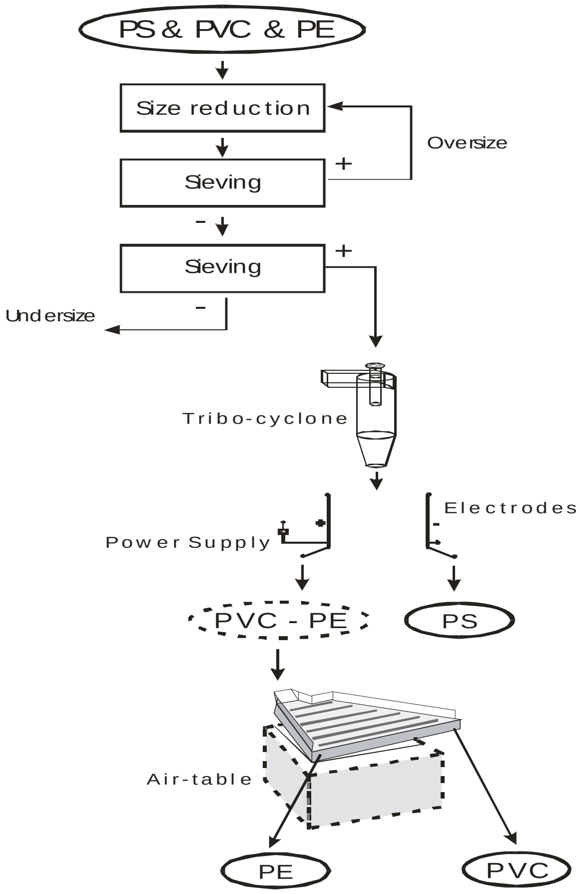

Figure 4. Simplified flowsheet of the process for separation of plastics according to their type.

On the other hand, a two-stage dry process that combines triboelectric separation and air tabling has been proposed for the separation of plastic wastes prior to mechanical recycling (option 2). It should be also noted that the data on the separation process were from the experimental work carried out by the authors and published elsewhere (Dodbiba, 2003). Figure 4 shows the simplified flowsheet of the process. A triboelectric separator can be employed for the first stage of the process to collect a PS-rich positively charged fraction and a PE/PVC negatively charged fraction. In the second stage, the PE/PVC fraction can be separated by means of an air table, by taking advantage of differences in specific gravities. It was estimated that the electricity requirement for this process, which is able to collect ca. 67 % of each plastic with a grade of 96 % or higher, is approximately 0.74 kWh/kg (Table 7). It is important to note that the rest of the plastics (middlings), which have not been recovered (i.e. less than 33 %), is not re-cycled in the system but is incinerated instead. In other words, the authors have chosen to calculate LCI for a mechanical recycling ratio (R_M) of 67 %. This was done in order to simplify the calculation of LCI. Nevertheless, should the recovery of plastics or the ratio of mechanical recycling be higher than 67 %, the middling can be re-processed to fulfill the requirement.

Next, the data on the processes are organized in vector notations in a way that resembles the classical input-output analysis (Leontief, 1970). The material balance principle and matrix algebra are combined to give an explicit formula (Heijungs, 1994):

$$g = BA^{-1} f \quad (1)$$

where g is the vector of the environmental loads; the matrix B represents the flow of environmental releases (CO_2 emission, etc.); the matrix A represents the flow of products and materials (electricity, materials usage, etc); the vector f (know as the demand vector) represents a special process where the functional unit (f_u) is the only output; the superscript –1 denotes that the matrix A is inverted.

The outcome of the inventory analysis (Eq. 1) is the vector g, which is a list containing the quantities g_i of pollutants released to the environment and the amount of energy and materials consumed during the life-cycle of plastics, i.e.:

$$g = \begin{pmatrix} g_1 \\ \vdots \\ g_i \\ \vdots \\ g_n \end{pmatrix} \quad \text{for} \quad i = 1, 2, \ldots, n \quad (2)$$

The results of the inventory analysis for each treatment option under the evaluation are given in Table 8.

3.3 Impact Assessment

Impact assessment, known as life cycle impact assessment (LCIA), the third phase in LCA (Fig. 2) is comprised of the following issues: (a) *selection* of environmental impact categories, such as abiotic resources, global warming, etc., (b) *classification*: assigning LCI results (the environmental loads g_i) to the environmental impact categories (classifying CO_2 emissions to global warming, etc.), (c) *characterization*: expressing LCA results in a way that can be compared (comparing the global warming impact of CO_2 and CH_4, etc.) and calculating the overall impact indicator of each impact category.

In this work, the environmental impact is assessed by calculating the impact indicator I_j of the following categories:

(1) *abiotic resources*, and

(2) *global warming*.

The impact indicators I_j are characterized using the following equations:

$$I_{i(j)} = g_i \times k_{i(j)} \quad , \quad i = 1,2,\ldots,n \quad (3)$$

$$I_j = \sum_{i=1}^{n} I_{i(j)} \quad , \quad j = 1,2,\ldots,q \quad (4)$$

In other words, the environmental loads g_i of the substances grouped in a category are expressed in terms of equivalent units by multiplying them by a characterization factor $k_{i(j)}$, (Eq. 3) (Guinee, 2002). The resulting impact indicators $I_{i(j)}$ are then aggregated to give an overall indicator I_j of the environmental impact category, (Eq. 4).

Table 8. Environmental loads, g_i

Category		Flow, g_i		Environmental loads	
				Energy Recovery: Option 1, (R_M = 0 %)	**Mechanical Recycling: Option 2,** (R_M = 67 %)
1	**Energy**	Energy from resources, (kcal)	$-g_{1,}$	-346,909,896,261	-248,122,522,246
2		Energy from combustion, (kcal)	g_2	188,101,440,000	62,073,475,213
3	**Depletion of resources**	Naphtha, (kg)	$-g_3$	-44,568,900	-14,707,737
4		Liquefied petroleum gas, (LPG), (kg)	$-g_4$	-904,594	-565,670
5		Natural gas liquid (NGL), (kg)	$-g_5$	-1,301,400	-429,462
6		Oxygen gas, (kg)	$-g_6$	-2,732,400	-901,692
7		Coal, (kg)	$-g_7$	-5,750,732	-10,783,713
8		Natural gas, (kg)	$-g_8$	-70,615	-132,417
9		Petroleum, (L)	$-g_9$	-1,406,271	-2,637,024
10		Crude oil, (L)	$-g_{10}$	-1,245,439	-2,335,434
11		Liquefied natural gas (LNG), (kg)	g_{11}	-4,935,517	-9,255,031
12	**Atmospheric emissions**	CO_2, (g)	g_{12}	451,228,644,294	334,343,918,629
13		CH_4, (g)	g_{13}	28,004,400	9,241,452
14		HCF, (g)	g_{14}	1,307	2,450
15		N_2O, (g)	g_{15}	1,301,351	755,622
16		SF_6, (g)	g_{16}	4,423	8,294
17		NO_x, (g)	g_{17}	235,265,346	207,984,924
18		SO_x, (g)	g_{18}	615,369,058	617,249,269
19		Dust, (g)	g_{19}	115,834,046	39,374,618
20		HCl, (g)	g_{20}	2,194,938	724,330
21		CO, (g)	g_{21}	117,936	38,919
22	**Waterborne emissions**	Chemical Oxygen Demand (COD), (mg)	g_{22}	7,363,397,955	2,453,219,626
23		T-P, (mg)	g_{23}	297,810,000	98,277,300
24		T-Ni, (mg)	g_{24}	7,236,000,000	2,387,880,000
25		Phenol, (mg)	g_{25}	30,807,000	10,166,310

3.3.1 Depletion of abiotic resources

Depletion of abiotic resources is assessed by calculating the *ADP* indicator (Eqs. 3 and 4). The *ADP* indicator indicates the extraction of non-renewable raw materials such as naphtha, natural gas, petroleum, crude oil, etc. Figure 5 shows the normalized $ADP_{(i)}$ indicators of various non-renewable raw materials extracted during the life-cycle of plastics needed for production of color TV sets.

A look at Figure 5 shows that the $ADP_{(i)}$ varies with the type of raw material and the treatment option for plastic wastes. It can be seen that naphtha is the resource depleted the most, consequently having the greatest environmental impact. It can also be seen that LNG and coal, which are used for production of electricity, have a relatively great environmental impact.

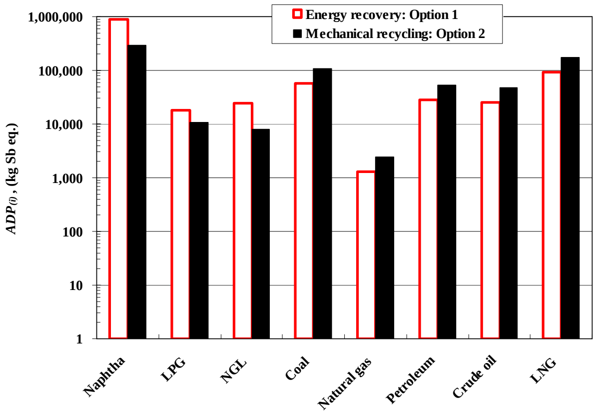

Figure 5. $ADP_{(i)}$ of various abiotic resources.

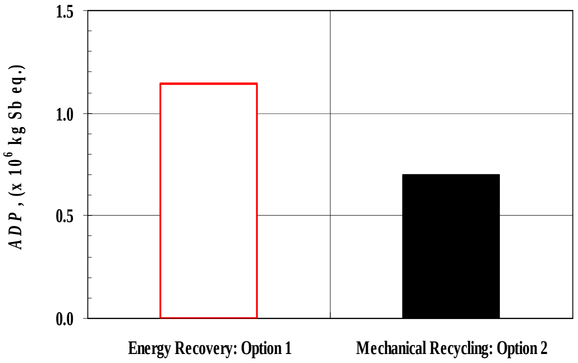

Figure 6. Depletion of abiotic resources, (*ADP*).

The normalized indicators $ADP_{(i)}$ are then combined to calculate the overall impact indicator of abiotic depletion (*ADP*) for each treatment option, $ADP=\Sigma ADP_{(i)}$ (Eq. 4). The results are given in Figure 6, which shows that separation of plastic wastes for mechanical recycling (option 2) has a lower environmental impact on the abiotic depletion when compared with incineration of plastics wastes for energy recovery (option 1).

3.3.2 Global warming

Global warming is assessed by calculating the *global warning potential*, *GWP* indicator (Eqs. 3 and 4). The *GWP* indicator indicates the amount of greenhouses gases emitted into the Earth's atmosphere. Figure 7 shows $GWP_{(i)}$ indicators of various greenhouses gases emitted during the life-cycle of plastics needed for production of color TV sets.

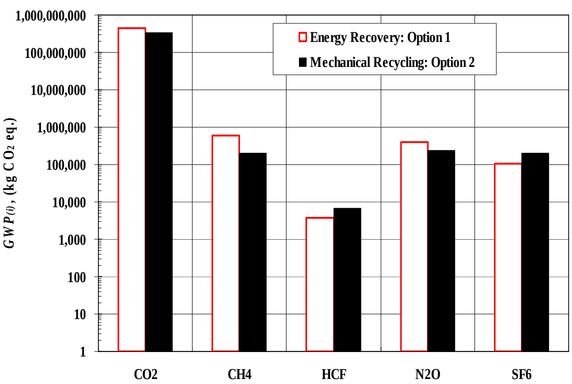

Figure 7. $GWP_{(i)}$ of various greenhouses gases.

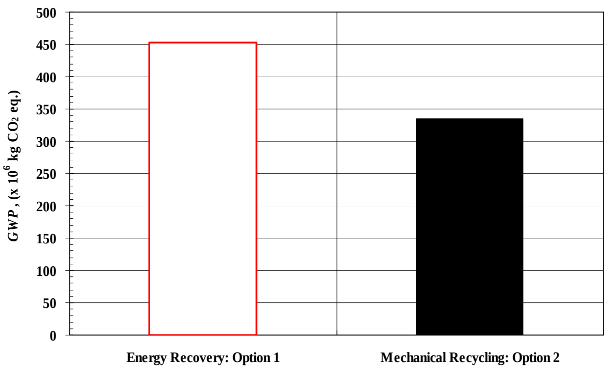

Figure 8. Global warming potential, (*GWP*).

A look at Figure 7 shows that the $GWP_{(i)}$ varies with the type of greenhouse gas and the treatment option for plastic wastes. It can be seen that the emission of CO_2 has the greatest environmental impact. It can also be seen that CH_4, which is mainly emitted during the production of PE, and NO_2 have a relatively great impact on global warming.

The normalized indicators $GWP_{(i)}$ are then combined to give the overall impact indicator of global warming

(*GWP*) for each treatment option, $GWP = \Sigma GWP_{(i)}$ (Eq. 4). The results are given in Figure 8, which shows that separation of plastic wastes for mechanical recycling (option 2) has a lower environmental impact on global warming.

3.4 Interpretation

Interpretation i.e. evaluation of results is the last phase of the LCA. The objective was to analyze results and reach conclusions based on the findings of the preceding phases of the LCA. Table 9 compares both of the environmental indicators that have been calculated for each treatment option under the assessment. It can be seen that both *ADP* and *GWP* indicators of option 2 are smaller when compared with those of option 1. These results indicated that the separation of plastics for mechanical recycling (option 2) is a more environmental-friendly alternative for treatment of plastic wastes from discarded color TV sets.

Table 9. Comparing the environmental indicators for energy recovery and mechanical recycling

Environmental Indicators	Option 1, (Energy recovery, R_M = 0 %)	Option 2, (Mechanical recycling, R_M = 67 %)
Abiotic depletion potential (*ADP*), kg Sb. eq.	1,143,091	698,156
Global warming potential (*GWP*), kg CO_2 eq.	452,329,521	334,977,313

4 CONCLUSIONS

The energy recovery and the mechanical recycling of plastic wastes from discarded TV sets are compared in the context of LCA. The results show that energy recovery is an option that uses more resources and emits a larger quantity of greenhouse gases because of the incineration of plastic wastes. The separation of plastics for mechanical recycling, on the other hand, is a more effective alternative because it consumes less energy and fewer resources as well as having a lower environmental impact on global warming.

5 ACKNOWLEDGEMENTS

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7. NOMENCLATURE

A	Technology matrix
B	Environmental matrix
f	Demand vector
f_u	Functional unit
g	Vector of environmental loads
g_i	Environmental load of substance i
$I_{i(j)}$	Impact indicator
I_j	Impact category indicator
$k_{i(j)}$	Characterization factor
R_M	Ratio of mechanical recycling, (%)
Subscripts	
i	Burden or substance released/extracted from environment
j	Environmental impact category
n	Number of burdens or substances released/extracted from environment
q	Number of environmental impact categories
Superscripts	
-1	Indicates that the respective matrix should be inverted