Life Cycle Assessment: A Tool for Evaluating and Comparing Different Treatment Options for Plastic Wastes

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Outline

1. LCA Methodology (ISO 14040)

2. LCA of Plastic Wastes from Discarded TV Sets

3. Concluding Remarks

Outline

1. **LCA Methodology (ISO 14040)**

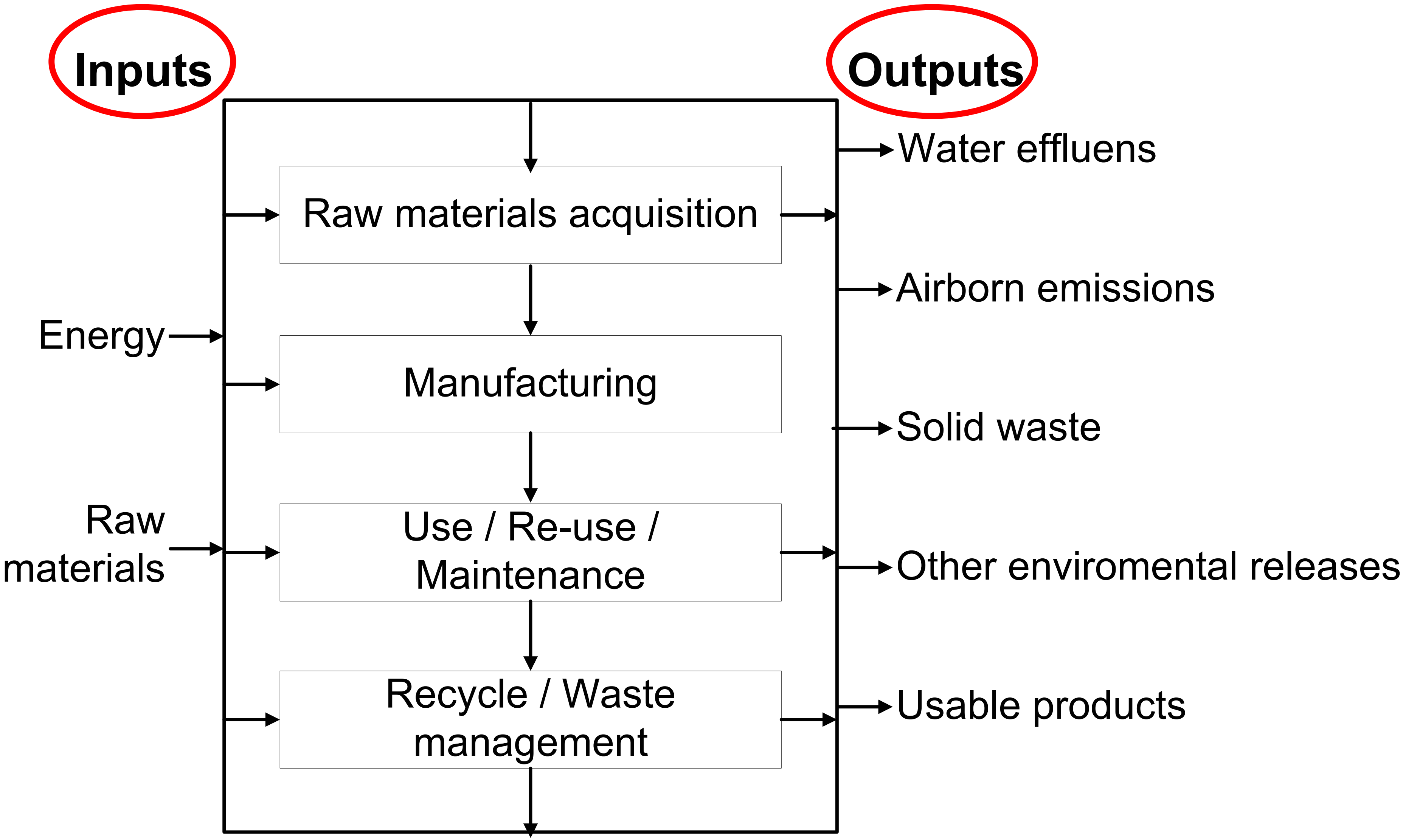
2. LCA of Plastic Wastes from Discarded TV Sets

3. Concluding Remarks

Scope of LCA

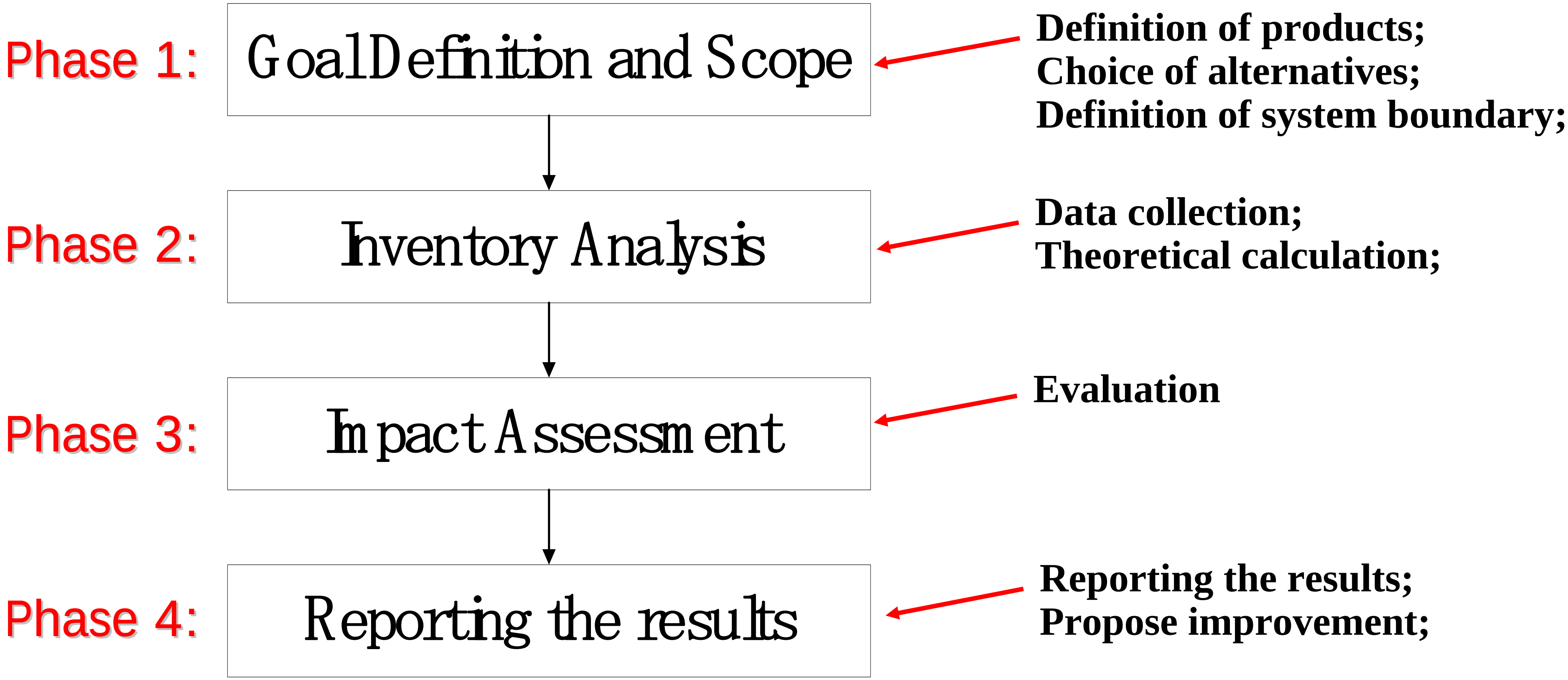
… to evaluate or compare the life cycle of "products"

Life-Cycle Stages and Boundaries



(**Source:** *EPA, 1993*)

Methodology:
Life Cycle Assessment, (ISO 14040)

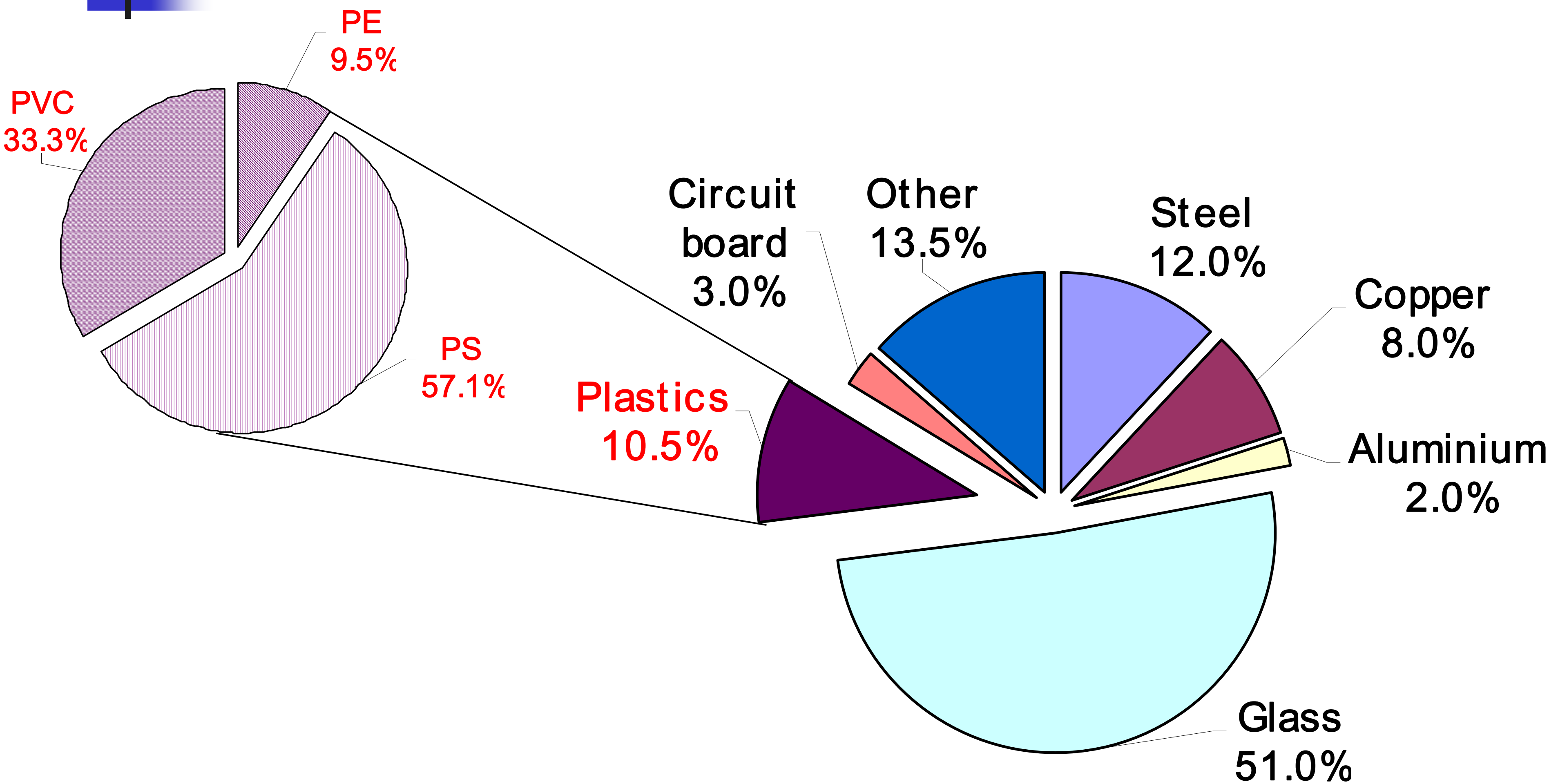


(**Source:** *Consoli et.al., 1993*)

Aim of Study

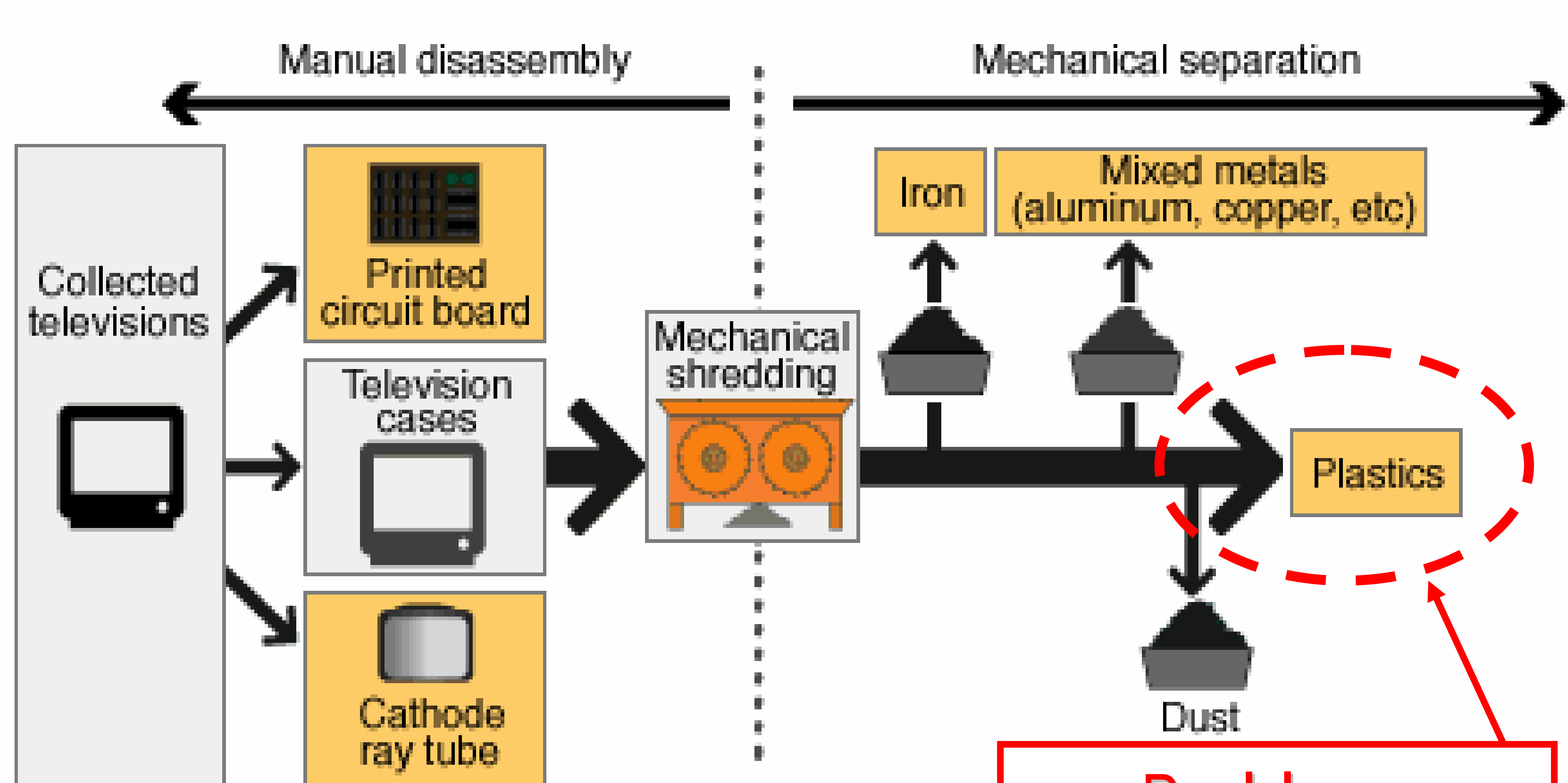
... to evaluate and compare
different recycling options
for plastic wastes from old TV sets
in context of LCA

Compositions of a TV Set (weight %)



(**Source:** *O. Murakami, Mitsubishi Elec. ADVANCE, pp. 6-9, 2001*).

Conventional Recycling System for TV sets



Problem:
How to recycle plastic wastes?

Source: *Association for Home Electrical Appliances of Japan*
http://www.aeha.or.jp/assessment/en/english_flame.html

Objective

… to compare two different recycling options for <u>plastic wastes</u> from old TV sets in context of <u>LCA</u>.

Option 1: ***Incineration*** of plastics for ***energy recovery*** (also known as thermal recycling)

Option 2: ***Sorting*** plastics for ***mechanical recycling*** (also know as material recycling)

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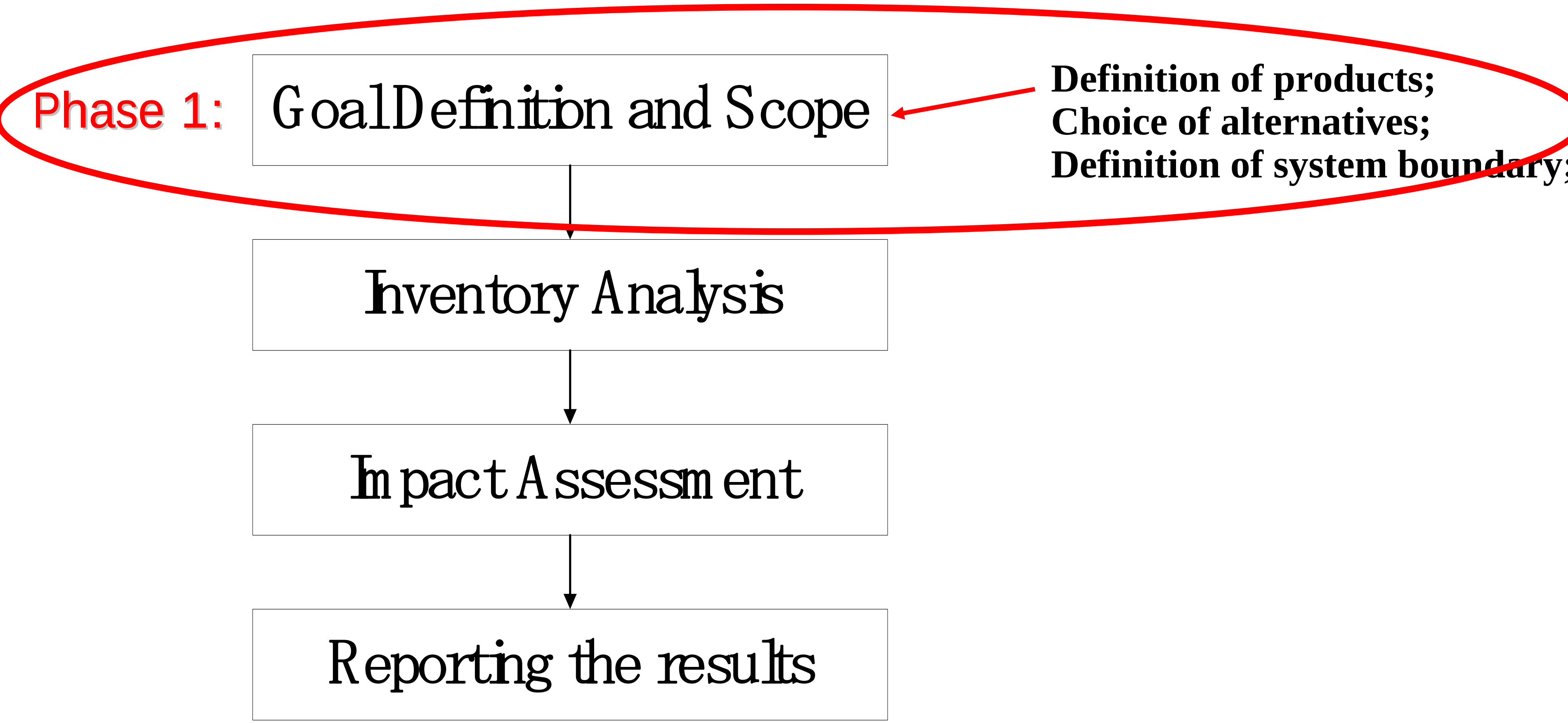


(**Source:** *Consoli et.al., 1993*)

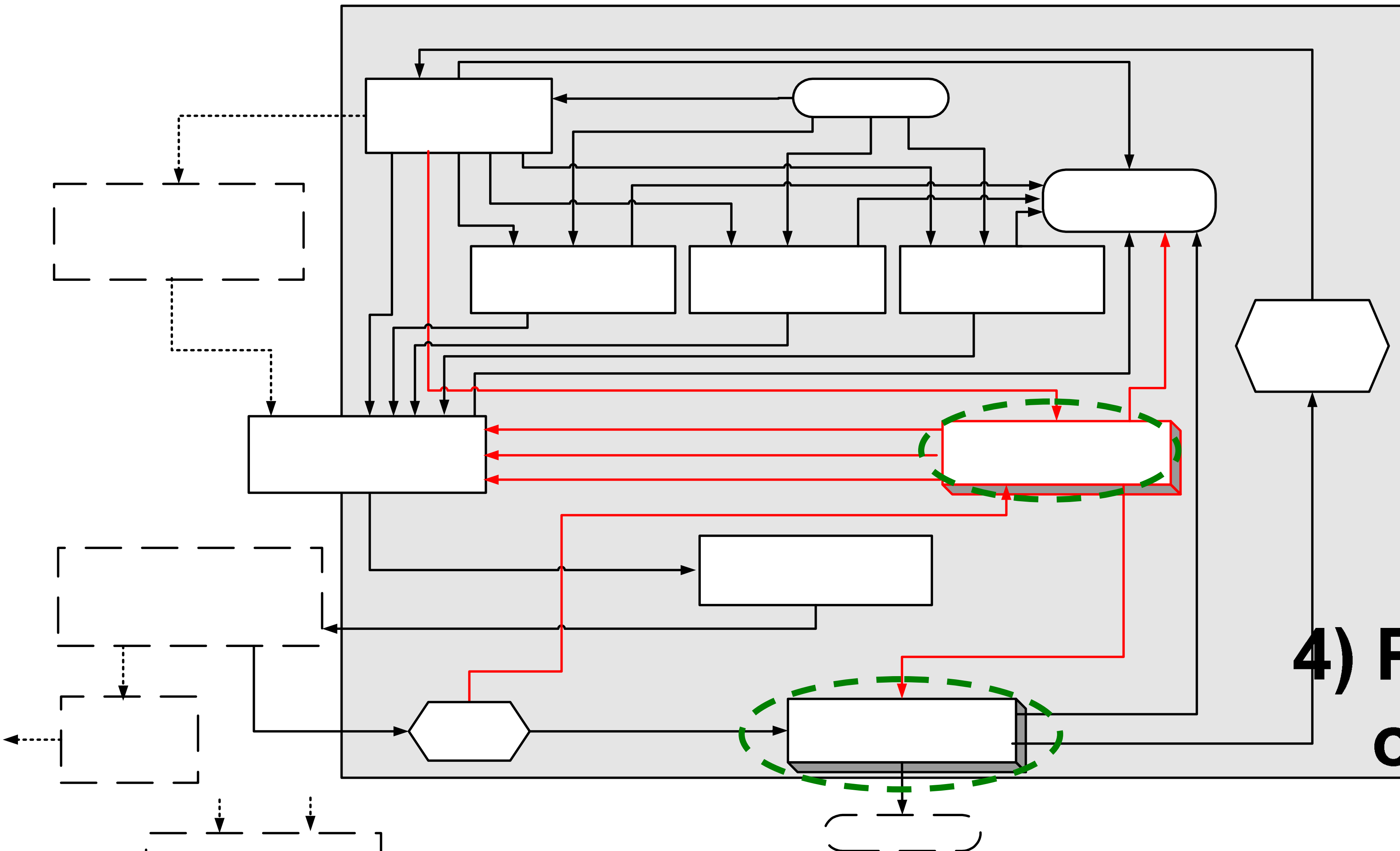
Phase 1 of LCA: Goal Definition and Scope

a. Subject of the study are plastic wastes from old TV sets (*display*: 25”, *weight* = 30 kg), which contain:

1. **PS** (6.0 wt%, i.e. 1.80 kg),
2. **PVC** (3.5 wt%, i.e. 1.05 kg),
3. **PE** (1.0 wt%, i.e. 0.30 kg).

b. Functional unit: is defined as **1.8 million** TV sets per year, over a period of **10 years.**

Life-cycle of plastics for TV sets



4) Pro
of

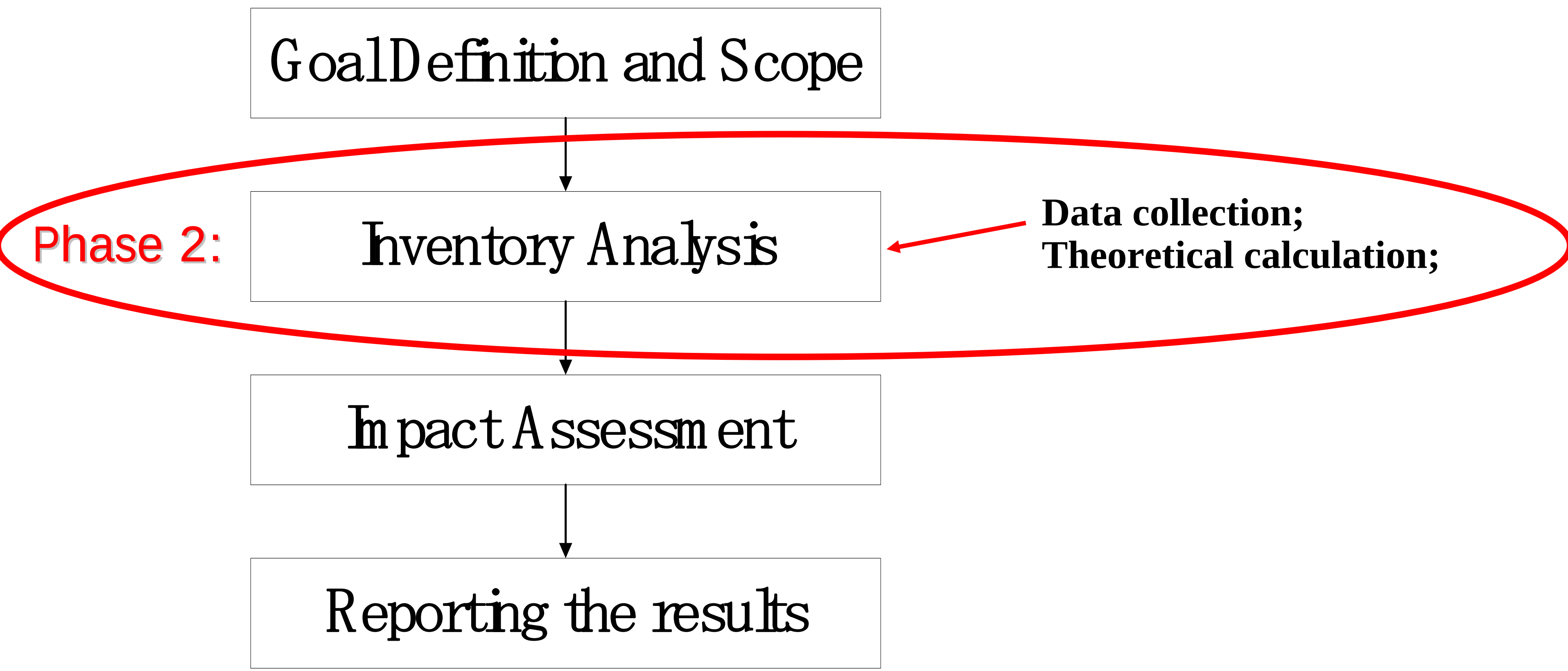
Special cases:

(1). Energy recovery, i.e. $c = 0\ \%$;

(2). Mechanical recycling, i.e. $c = 100\ \%$ and $r = 67\ \%$

Production of Steel,

Methodology:
Life Cycle Assessment, (ISO 14040)



(**Source:** ***Consoli et.al., 1993***)

Phase 2 of LCA: Inventory analysis
a) Data collection

The data of the processes, namely:

1. **production of PS,**
2. **production of PVC,**
3. **production of PE,**
4. **production of electricity,**
5. **production of a TV set,**

were from the LCA database of the Japan Environmental Management Association for Industry (**JEMAI**).

Phase 2 of LCA: Inventory analysis
a) Data collection

Option 1: Incineration of 1 kg plastic material

Energy generated:

PS – 9,604 kcal/kg
PVC – 4,300 kcal/kg
PE – 11,140 kcal/kg

Source: ***K. Krekeler et al., Kunstsoffe, 55/10, pp. 758, 1965***

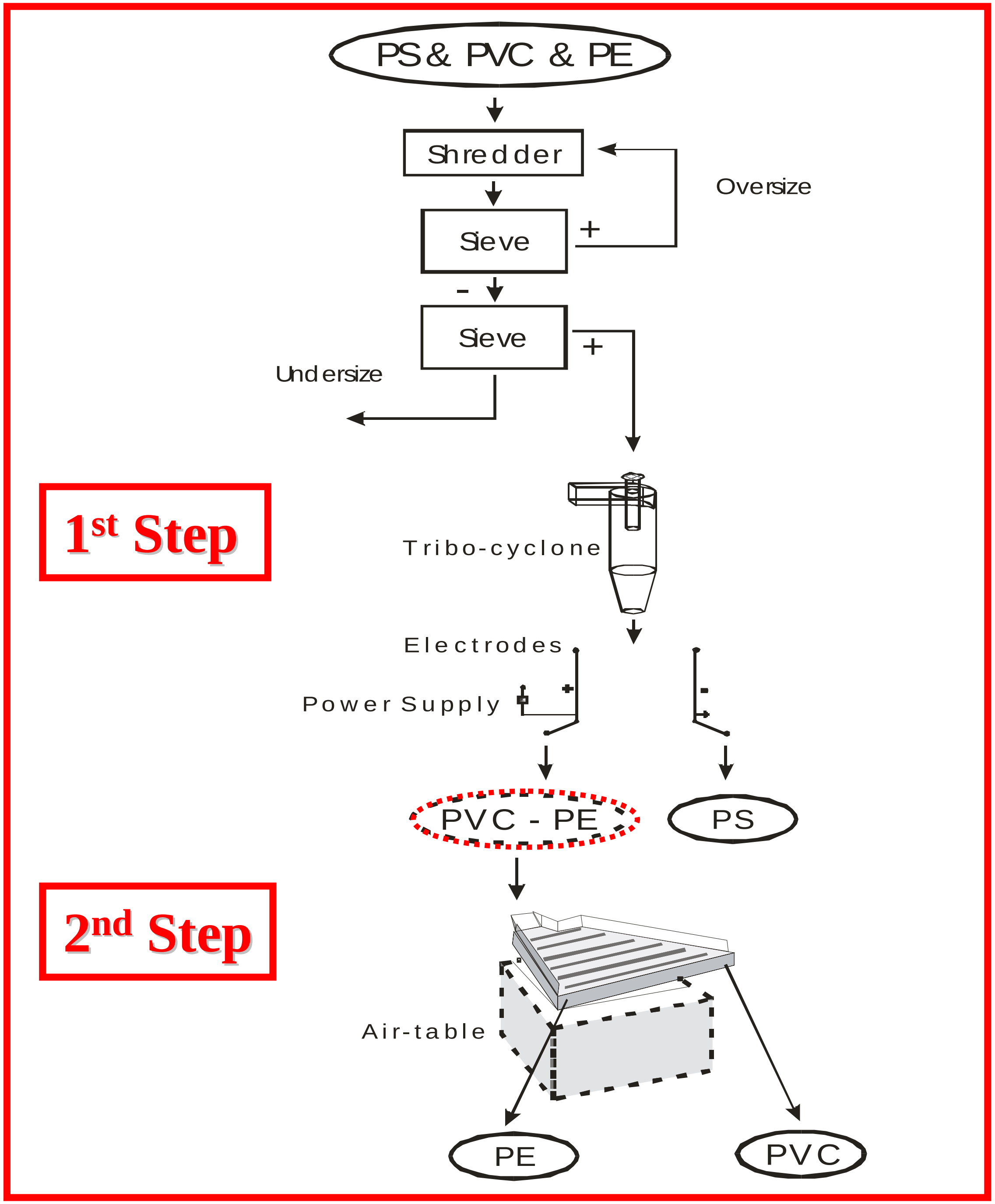
Emission:

2,640 g CO_2 /kg

Source: ***Ministry of Environment of Japan, Guidelines, 2004***

Option 2: Separation of plastic wastes prior to mechanical recycling

Plastics	Density, [kg/m^3]
PS	1050
PE	960
PVC	1400



Phase 2 of LCA: Inventory analysis
a) Data collection

Option 2: Separation of plastic wastes
(by combining triboelectric separation and air tabling)

Energy: 0. 74 kWh/kg

Triboelectric separator	0.04 kWh/kg
Air table	0.66 kWh/kg
Size reduction	0.02 kWh/kg
Sieving	0.02 kWh/kg

Recovery of products: 67 %

Grade of products: > 95 %

Phase 2 of LCA: Inventory analysis
b) Theoretical calculations

g is the vector of the environmental interventions

the matrix ***A*** represents the flow of products and materials

$$[g] = [B] \times [A^{-1}] \times [f]$$

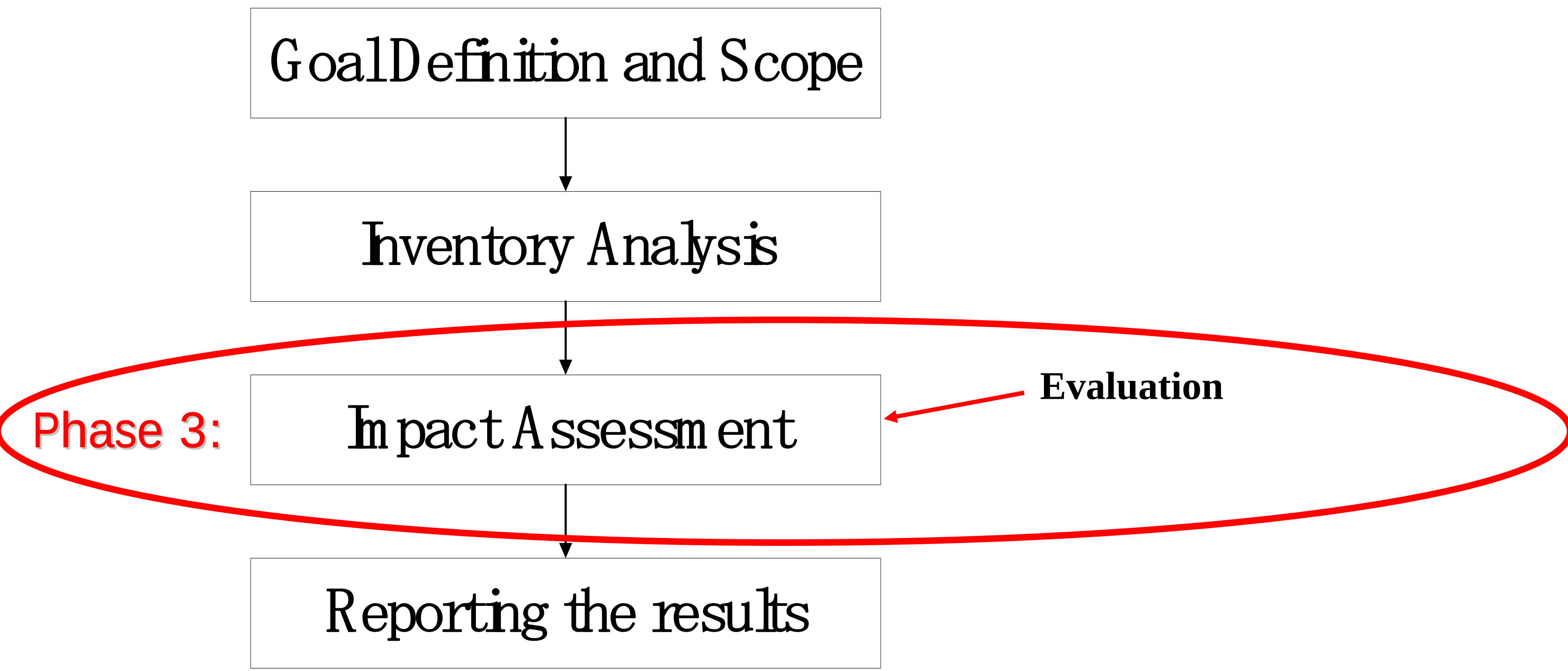
the matrix ***B*** represents the flow of environmental loads

the vector ***f*** represents a special process where the functional unit is an output

Steps to be followed in theoretical calculation:

1. Calculate the inverse of matrix of ***A*** (i.e. A^{-1})
2. Calculate the inventory vector ***g***

Methodology:
Life Cycle Assessment, (ISO 14040)



(**Source:** ***Consoli et.al., 1993***)

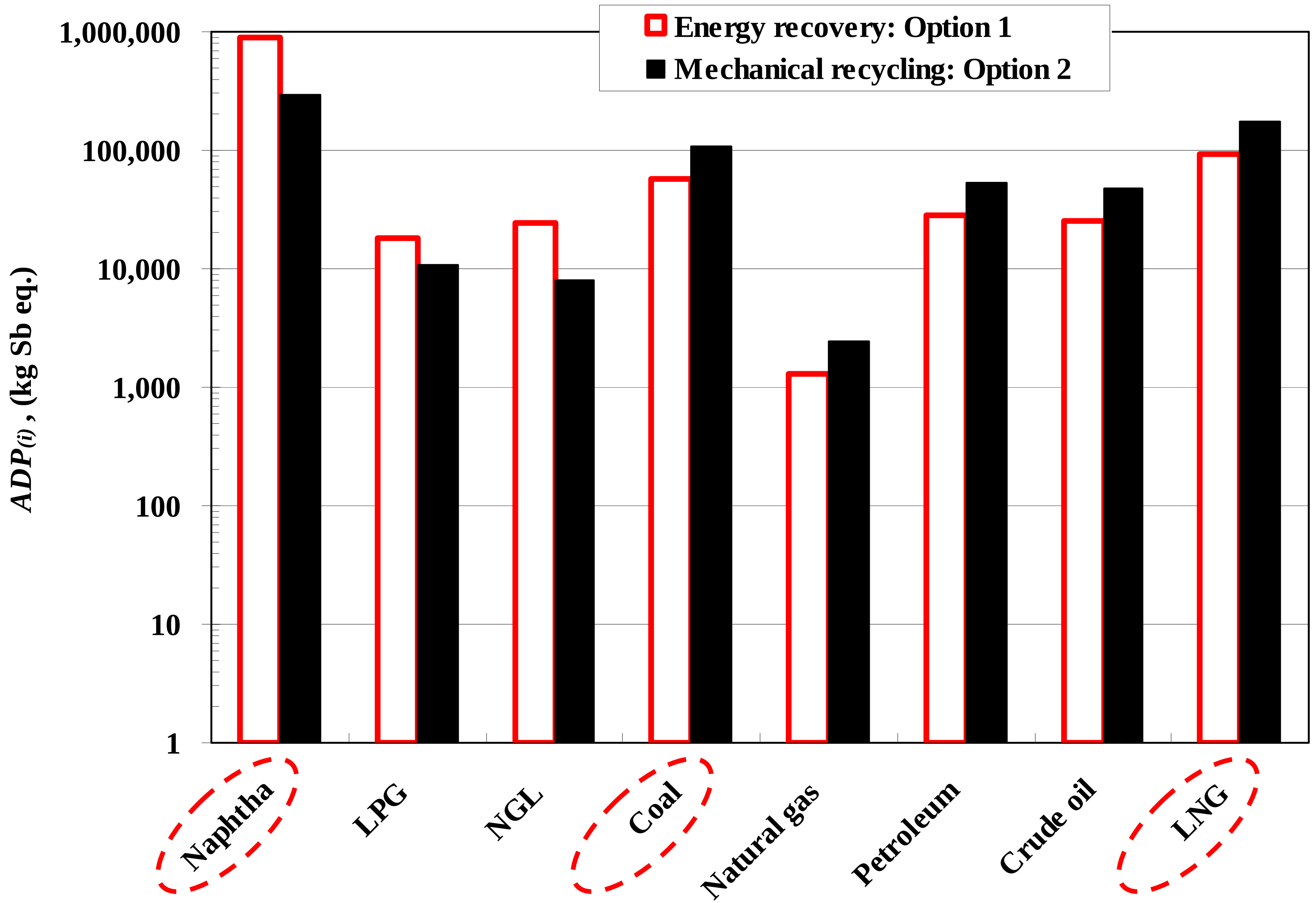
Phase 3 of LCA: Impact assessment

The categories of the environmental impacts:

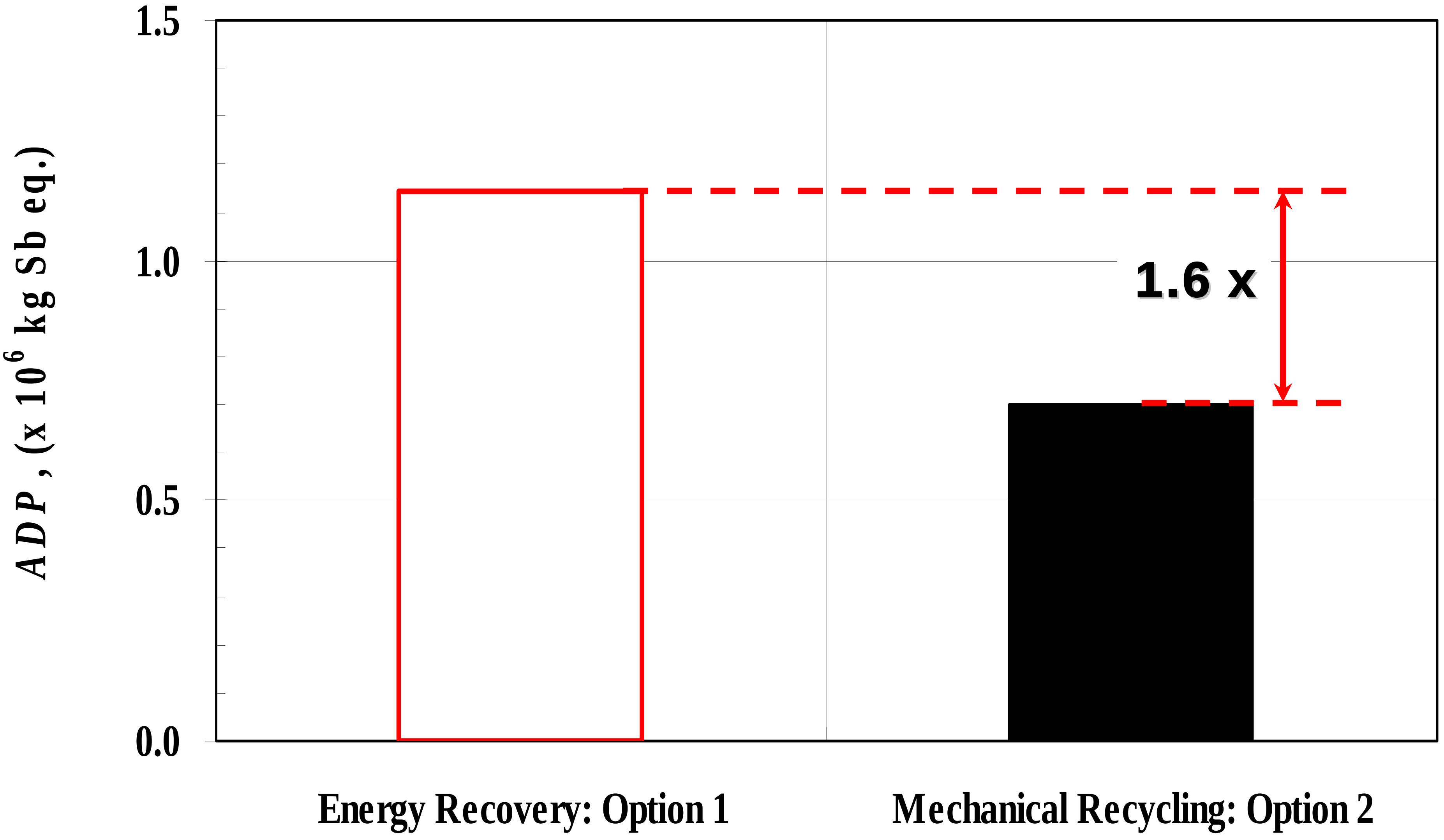
a) Abiotic resources: **ADP** (in kg Sb eq.)

b) Global warming: **GWP** (in kg CO_2 eq.)

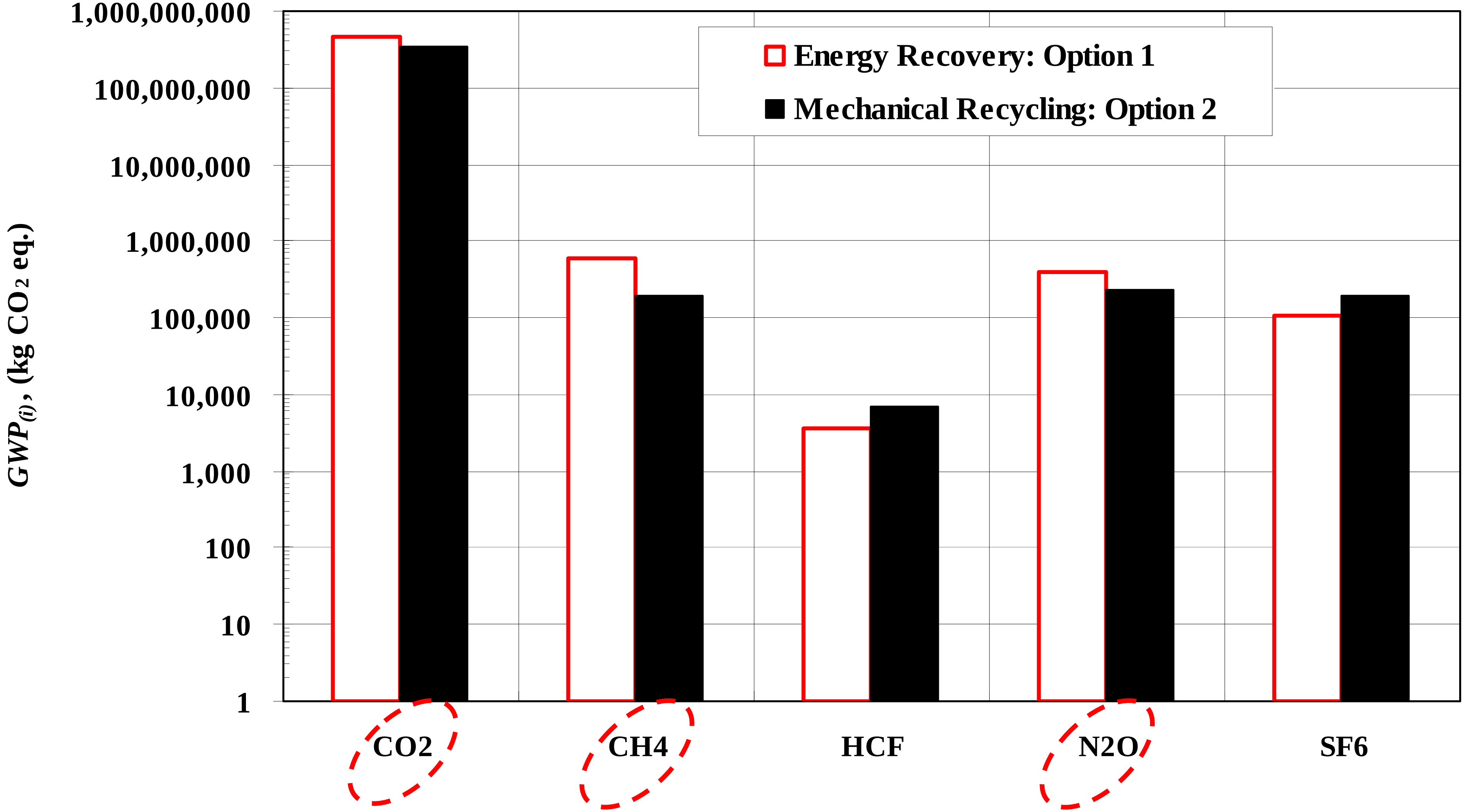
Phase 3 of LCA: Impact assessment
a) Depletion of Abiotic Resources, (ADP)



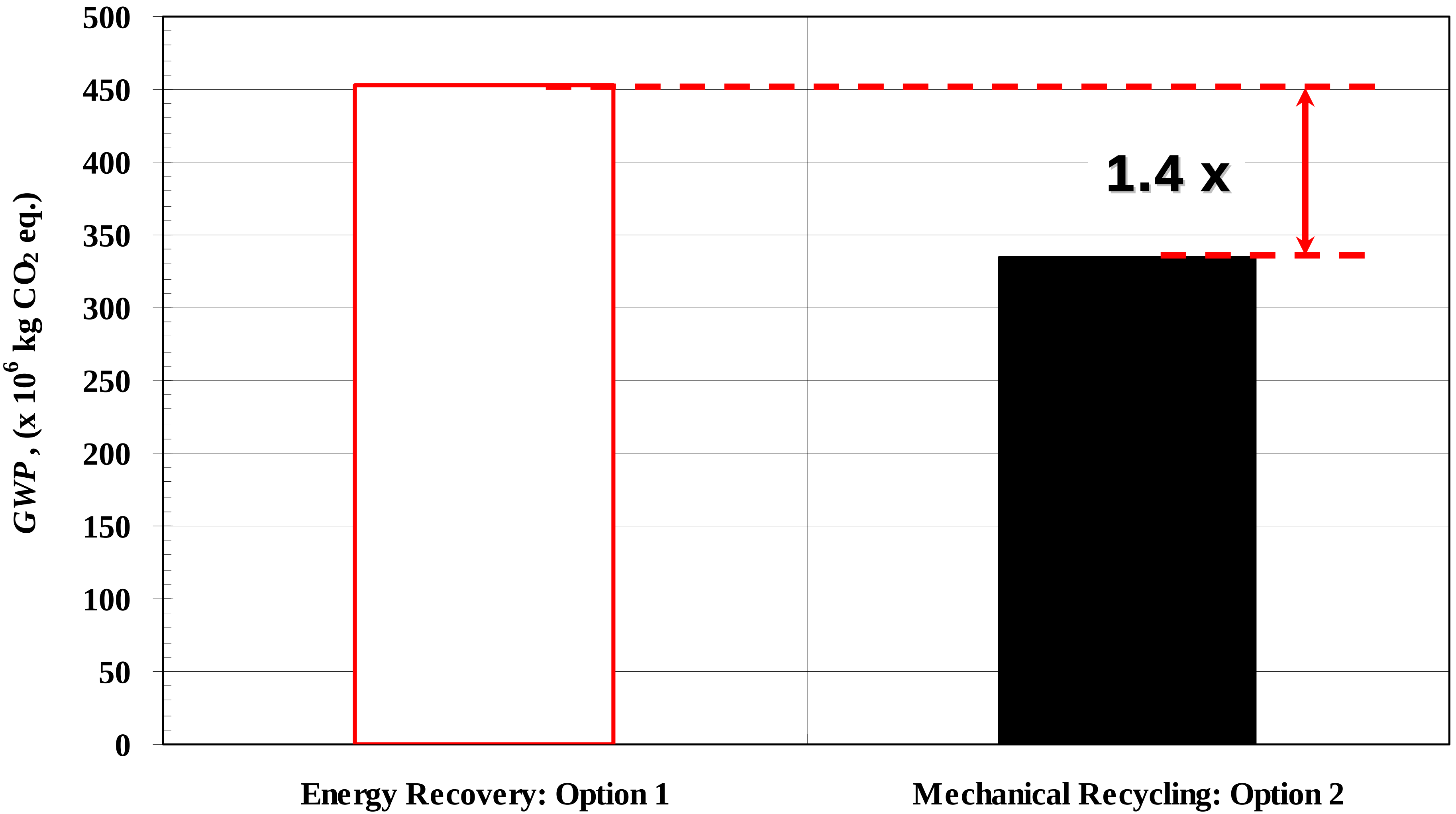
Phase 3 of LCA: Impact assessment
a) Depletion of Abiotic Resources, (ADP)



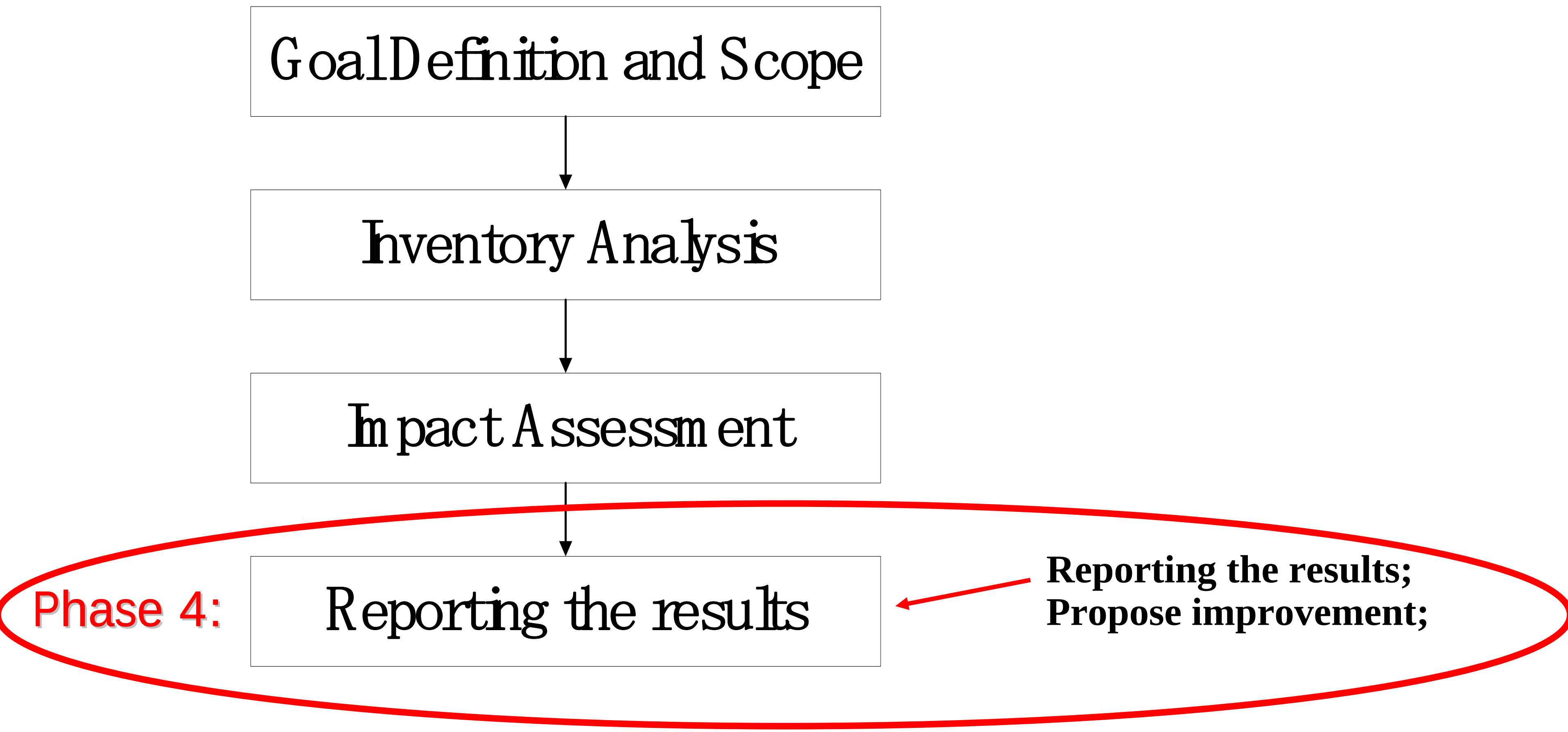
Phase 3 of LCA: Impact assessment
b) Global Warming Potential (GWP)



Phase 3 of LCA: Impact assessment
b) Global Warming Potential (GWP)

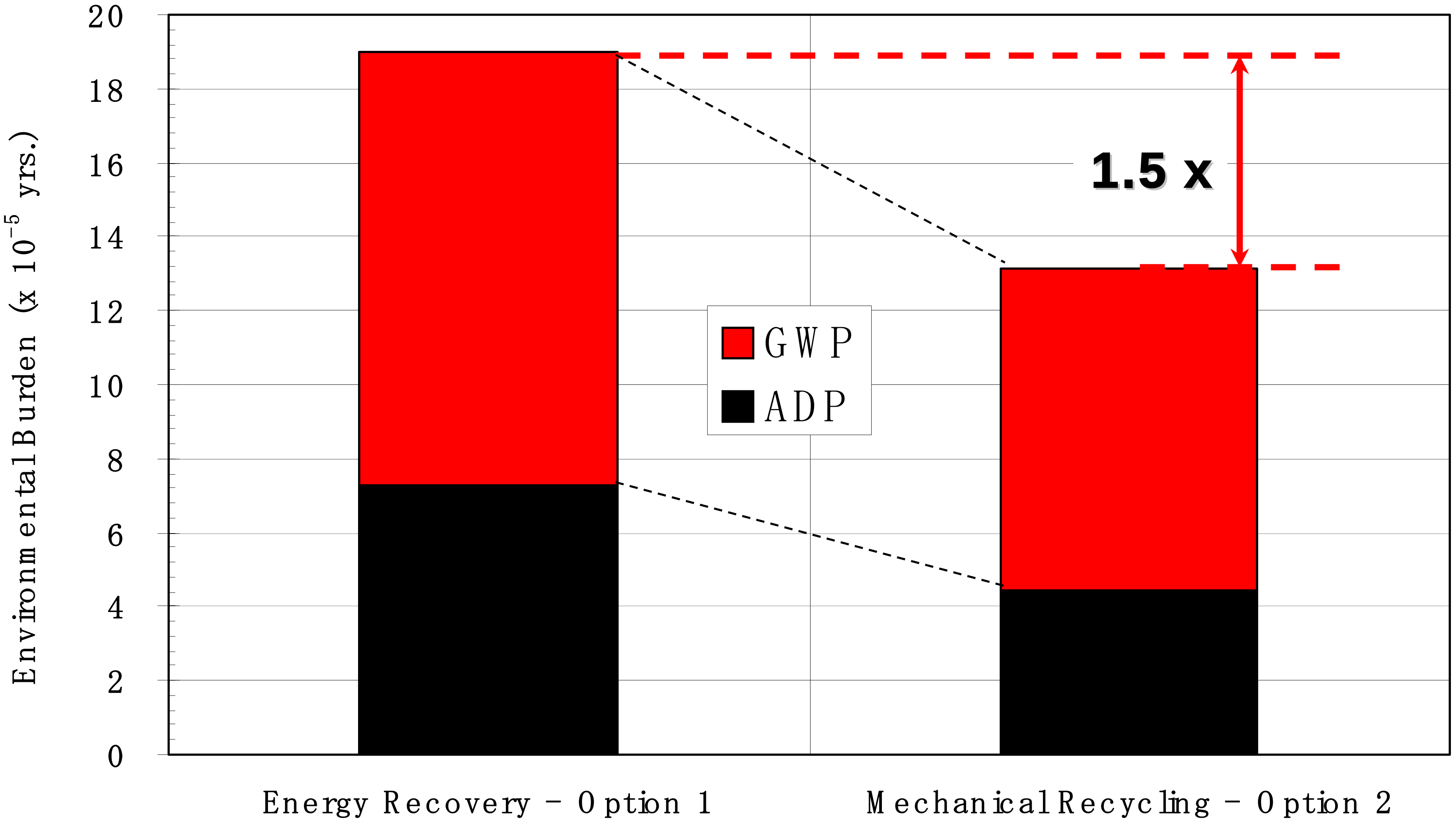


Methodology:
Life Cycle Assessment, (ISO 14040)



(**Source:** ***Consoli et.al., 1993***)

Phase 4 of LCA: Main Results
Environmental Impact



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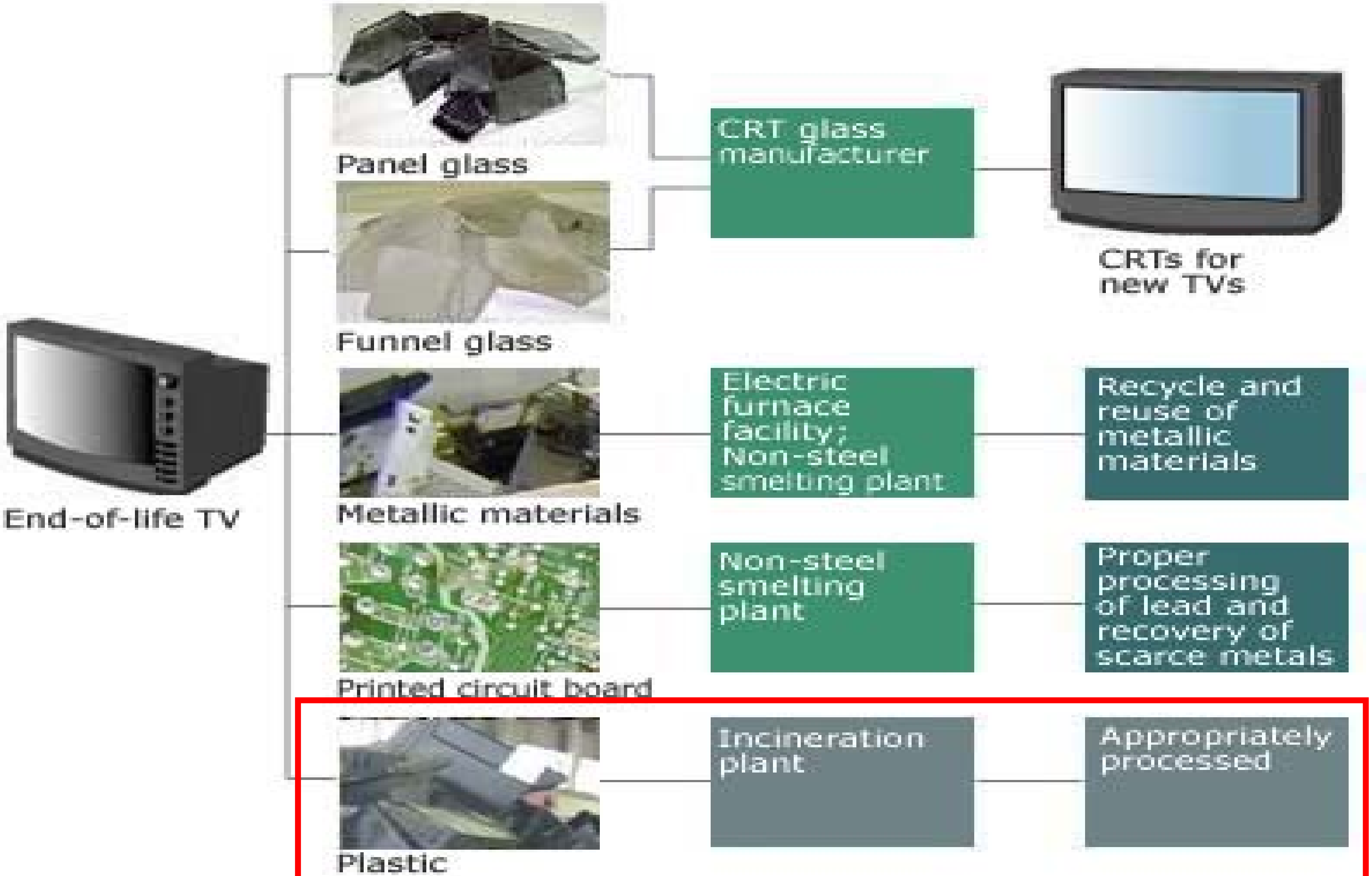
Concluding Remarks

- The ***energy recovery*** (***option 1***) and the ***mechanical recycling*** (***option 2***) of **plastic wastes** from the discarded TV sets were compared in the context of **LCA**.
- The **energy recovery** is an treatment option that generated more energy due to the incineration of plastic wastes. Nevertheless, this option also uses more resources and emits a larger quantity of greenhouse gases.
- The separation of plastics for **mechanical recycling** is more effective alternative, because it consumes fewer energy and resources, as well as has a lower environmental impact on global warming.

Conventional Recycling System for TV sets



Source: Matsushita Eco Technology Center (METEC)
Available from internet: http://panasonic.co.jp/eco/en/metec/tv/material2-1.html

Three alternatives are being considered when dealing with plastic wastes:

1. ***energy recovery*** (also known 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;

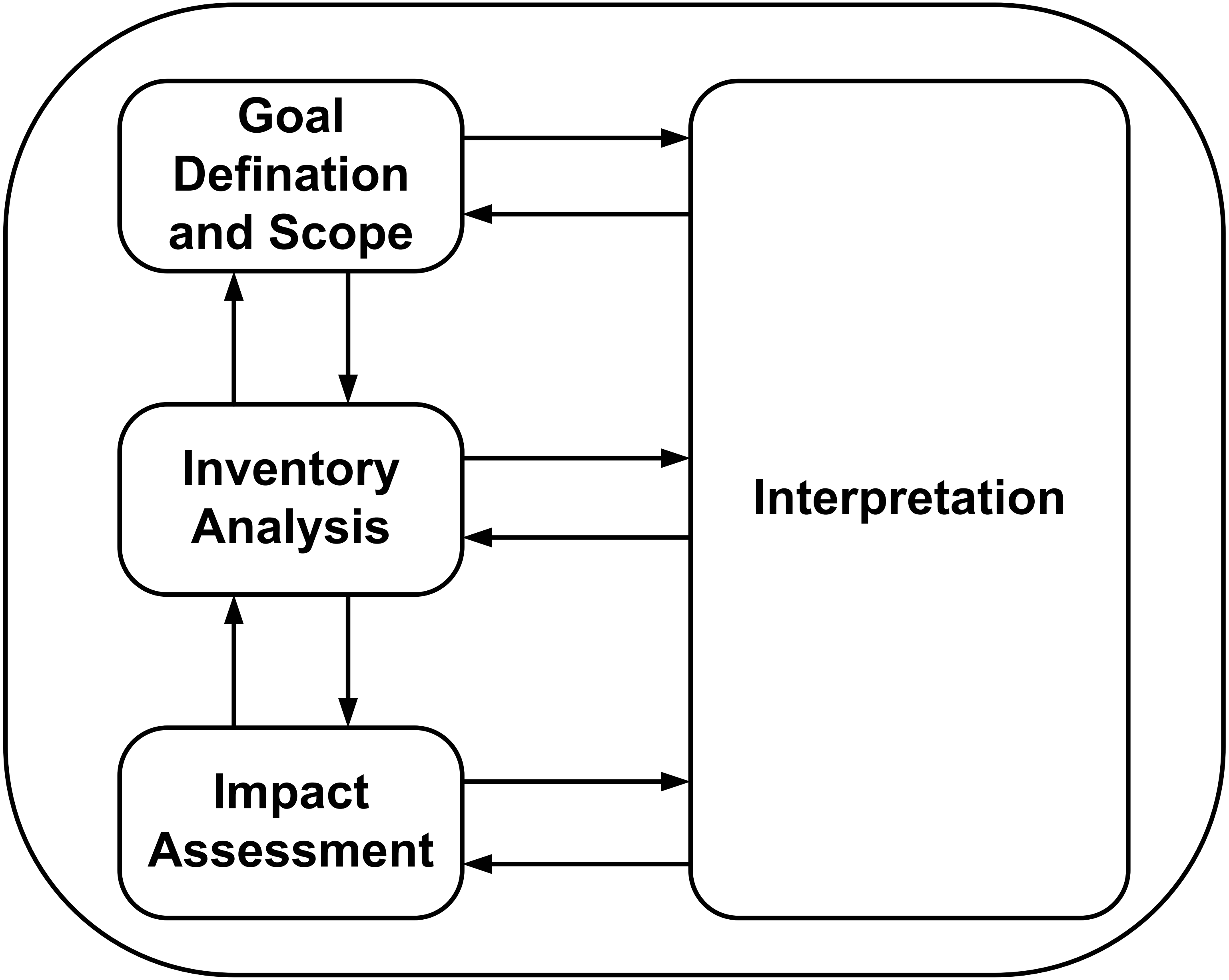
3. ***feedstock recycling*** (also known as chemical recycling), i.e. the technique that break down polymers into their constituent monomers, which in turn can be used again in refineries or petrochemical and chemical production.

Required Purity of Sorted Plastics for Reuse

(courtesy of KINKI KOGYO Co. Ltd., Japan)

- Reuse of plastics in circulating system as low grade plastics : > 95.0 %
- Reuse of plastics in circulating system as virgin plastics : > 99.5 %
- Reuse of plastics for agricultural, horticultural industry, etc. : > 99.0 %
- Use of plastics as oxidant in blast furnaces : < 1.0 % (PVC impurity)

Life Cycle Assessment Framework



(**Source:** *LCA, ISO 14040*)

Bond's Method: Size-reduction

$$W = 10\,W_i\left(\frac{1}{\sqrt{D_P}} - \frac{1}{\sqrt{D_F}}\right)$$

W_i = 13.81 kWh/t

D_P = 2.63 mm

D_F = 5.00 mm

Production of 1 kg PS

(Source: JEMAI-LCA On-line Database)

Category	Flow	Substances	Production of PS
Economic Output / Unit Process	$a_{1,1}$	PS, (kg)	1
Economic inflow	$b_{1,1}$	Energy, (kcal)	4567.1
	$a_{4,1}$	Electric power, kWh	0.133
	$b_{3,1}$	Naphtha, (kg)	0.962
	$b_{4,1}$	LPG, (kg)	0.014
	$b_{5,1}$	NGL, (kg)	0.025
	$b_{6,1}$	Oxygen gas, (kg)	0.012
Environmental load substance (atmosphere)	$b_{12,1}$	CO_2 (g)	1387
	$b_{13,1}$	CH_4, (g)	0.031
	$b_{15,1}$	N_2O, (g)	0.0002
	$b_{17,1}$	NO_x, (g)	1.24
	$b_{18,1}$	SO_x, (g)	0.262
	$b_{19,1}$	Dust, (g)	0.0349
	$b_{20,1}$	HCl, (g)	0.0006
Environmental load substance (water quality)	$b_{22,1}$	COD, (mg)	64.8
	$b_{23,1}$	T-P, (mg)	4.2
	$b_{24,1}$	T-Ni, (mg)	119
	$b_{25,1}$	Phenol, (mg)	0.1

Production of 1 kg PVC

(Source: JEMAI-LCA On-line Database)

Category	Flow	Substances	Production of PVC
Economic Output / Unit Process	$a_{2,2}$	PVC, (kg)	1
Economic inflow	$b_{1,2}$	Energy, (kcal)	4937.9
	$a_{4,2}$	Electric power, kWh	0.29
	$b_{3,2}$	Naphtha, (kg)	0.435
	$b_{4,2}$	LPG, (kg)	0.009
	$b_{5,2}$	NGL, (kg)	0.016
	$b_{6,2}$	Oxygen gas, (kg)	0.124
Environmental load substance (atmosphere)	$b_{12,2}$	CO_2 (g)	1105
	$b_{15,2}$	N_2O, (g)	0.0002
	$b_{17,2}$	NO_x, (g)	1.01
	$b_{18,2}$	SO_x, (g)	0.313
	$b_{19,2}$	Dust, (g)	0.0296
	$b_{20,2}$	HCl, (g)	0.00082
	$b_{21,2}$	CO (g)	0.00624
Environmental load substance (water quality)	$b_{22,2}$	COD, (mg)	268
	$b_{23,2}$	T-P, (mg)	7.7
	$b_{24,2}$	T-Ni, (mg)	152
	$b_{25,2}$	Phenol, (mg)	1.43

Production of 1 kg PE

(Source: JEMAI-LCA On-line Database)

Category	Flow	Substances	Production of PE
Economic Output / Unit Process	$a_{3,3}$	PE, (kg)	1
Economic inflow	$b_{1,3}$	Energy, (kcal)	3540.8
	$a_{4,3}$	Electric power, kWh	0.08
	$b_{3,3}$	Naphtha, (kg)	0.959
	$b_{4,3}$	LPG, (kg)	0.02
	$b_{5,3}$	NGL, (kg)	0.035
Environmental load substance (atmosphere)	$b_{12,3}$	CO_2 (g)	980.35
	$b_{13,3}$	CH_4, (g)	5
	$b_{15,3}$	N_2O, (g)	0.2
	$b_{17,3}$	NO_x, (g)	0.942
	$b_{18,3}$	SO_x, (g)	0.217
	$b_{19,3}$	Dust, (g)	21
	$b_{20,3}$	HCl, (g)	0.4
Environmental load substance (water quality)	$b_{22,3}$	COD, (mg)	34
	$b_{23,3}$	T-P, (mg)	3
	$b_{24,3}$	T-Ni, (mg)	94
	$b_{25,3}$	Phenol, (mg)	0.1

Production of 1 kWh Electricity

(Source: JEMAI-LCA On-line Database)

Category	Flow	Substance	Amount
Economic Output	$a_{4,4}$	Electricity, (kWh)	1
Economic inflow	$b_{4,4}$	LPG (kg)	0.00172
	$b_{7,4}$	Coal (kg)	0.05721
	$b_{8,4}$	Natural gas (kg)	0.0007025
	$b_{9,4}$	Petroleum (L)	0.01399
	$b_{10,4}$	Crude oil (L)	0.01239
	$b_{11,4}$	LNG (kg)	0.0491
Environmental load substance (atmosphere)	$b_{12,4}$	CO_2 (g)	353
	$b_{14,4}$	HCF (g)	0.000013
	$b_{15,4}$	N_2O (g)	0.0021
	$b_{16,4}$	SF_6 (g)	0.000044
	$b_{17,4}$	NO_x (g)	0.18
	$b18,4$	SO_x (g)	0.14
	$b_{19,4}$	Dust (g)	0.0074
Environmental load substance (water quality)	$b_{22,4}$	COD, (mg)	0.15

Production of a TV set

(Sources: a. JEMAI-LCA On-line Database; b. Murakami, 2001)

Category	Flow	Substance	Amount
Economic output	$a_{5,5}$	TV set, (No.)	1
Economic inflow	$a_{1,5}$	PS, (kg)	1.80
	$a_{2,5}$	PVC, (kg)	1.05
	$a_{3,5}$	PE, (kg)	0.30
	$a_{4,5}$	Electricity, (kWh)	9.4
Environmental load substance (atmosphere)	$b_{12,5}$	CO_2 (g)	10830
	$b_{17,5}$	NO_x (g)	8.49
	$b_{18,5}$	SO_x (g)	32.54

Matrix *B* of Environmental interventions

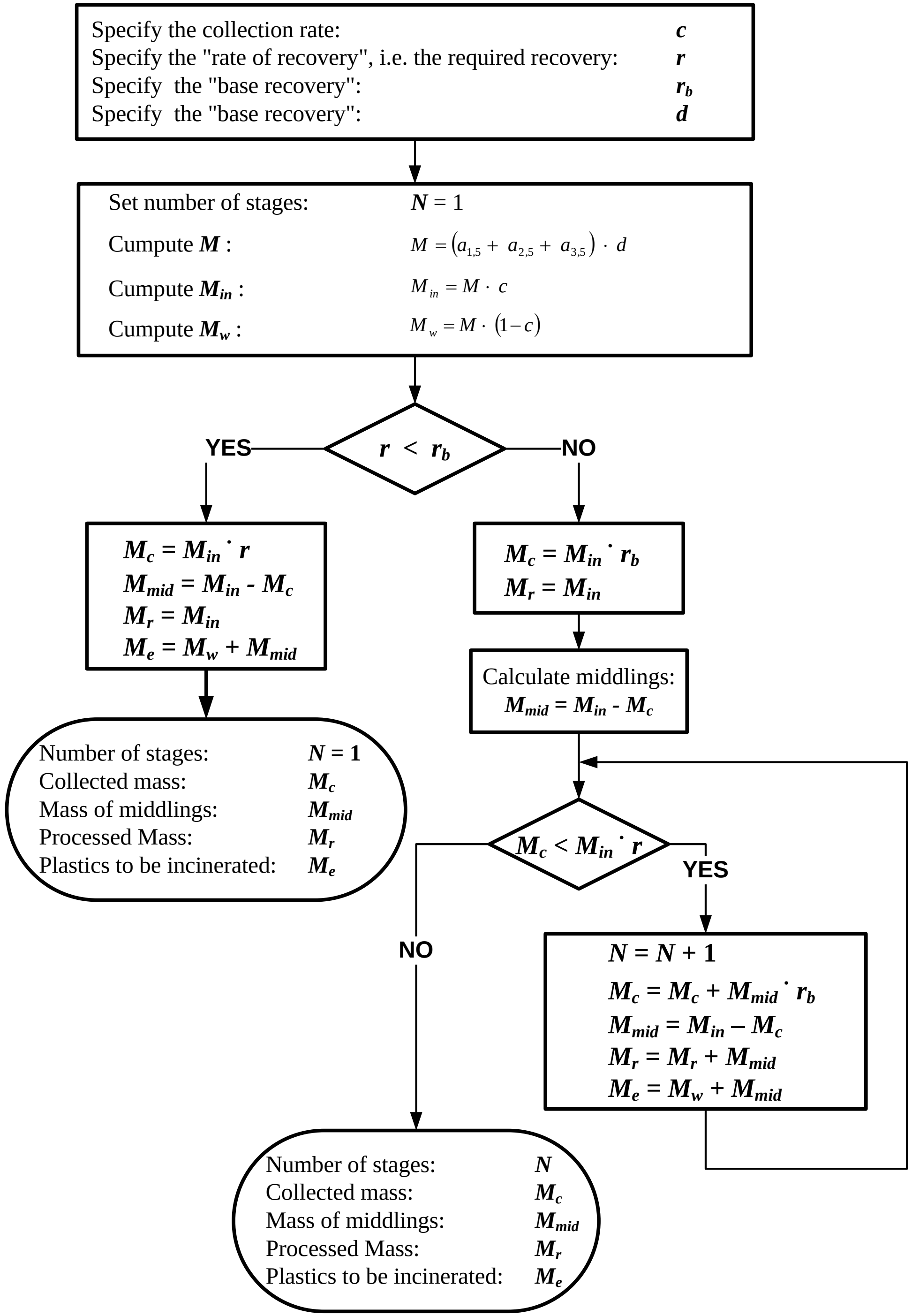
Flow		p - Process vector							
		1	2	3	4	5	6	7	8
		Production of PS (1 kg)	Production of PVC (1 kg)	Production of PE (1 kg)	Production of electricity	Production of TV set	Use of TV set (unit/yrs)	Incineration of Plastics	Recovery of plastics
1	Energy from resources, (kcal)	$-b_{1,1}$	$-b_{1,2}$	$-b_{1,3}$	0	0	0	0	0
2	Energy from combustion, (kcal)	0	0	0	0	0	0	$c \cdot d(1-r)\frac{(a_{1,5} \cdot H_1 + a_{2,5} \cdot H_2 + a_{3,5} \cdot H_3)}{a_{5,5}}$	0
3	Naphtha, (kg)	$-b_{3,1}$	$-b_{3,2}$	$-b_{3,3}$	0	0	0	0	0
4	Liquefied petroleum gas, (LPG), (kg)	$-b_{4,1}$	$-b_{4,2}$	$-b_{4,3}$	$-b_{4,4}$	0	0	0	0
5	Natural gas liquid (NGL), (kg)	$-b_{5,1}$	$-b_{5,2}$	$-b_{5,3}$	0	0	0	0	0
6	Oxygen gas, (kg)	$-b_{6,1}$	$-b_{6,2}$	0	0	0	0	0	0
7	Coal, (kg)	0	0	0	$-b_{7,4}$	0	0	0	0
8	Natural gas, (kg)	0	0	0	$-b_{8,4}$	0	0	0	0
9	Petroleum, (L)	0	0	0	$-b_{9,4}$	0	0	0	0
10	Crude oil, (L)	0	0	0	$-b_{10,4}$	0	0	0	0
11	Liquefied natural gas (LNG), (kg)	0	0	0	$-b_{11,4}$	0	0	0	0
12	CO_2, (g)	$b_{12,1}$	$b_{12,2}$	$b_{12,3}$	$b_{12,4}$	$b_{12,5}$	0	$b_{12,8}\left[\frac{(a_{1,5} + a_{2,5} + a_{3,5})d\,(1 - c\,r)}{a_{5,5}}\right]$	0
13	CH_4, (g)	$b_{13,1}$	0	$b_{13,3}$	0	0	0	0	0
14	HCF, (g)	0	0	0	$b_{14,4}$	0	0	0	0
15	N_2O, (g)	$b_{15,1}$	$b_{15,2}$	$b_{15,3}$	$b_{15,4}$	0	0	0	0
16	SF_6, (g)	0	0	0	$b_{16,4}$	0	0	0	0
17	NO_x, (g)	$b_{17,1}$	$b_{17,2}$	$b_{17,3}$	$b_{17,4}$	$b_{17,5}$	0	0	0
18	SO_x, (g)	$b_{18,1}$	$b_{18,2}$	$b_{18,3}$	$b_{18,4}$	$b_{18,5}$	0	0	0
19	Dust, (g)	$b_{19,1}$	$b_{19,2}$	$b_{19,3}$	$b_{19,4}$	0	0	0	0
20	HCl, (g)	$b_{20,1}$	$b_{20,2}$	$b_{20,3}$	0	0	0	0	0
21	CO, (g)	0	$b_{21,2}$	0	0	0	0	0	0
22	Chemical Oxygen Demand (COD), (mg)	$b_{22,1}$	$b_{22,2}$	$b_{22,3}$	$b_{22,4}$	0	0	0	0
23	T-P, (mg)	$b_{23,1}$	$b_{23,2}$	$b_{23,3}$	0	0	0	0	0
24	T-Ni, (mg)	$b_{24,1}$	$b_{24,2}$	$b_{24,3}$	0	0	0	0	0

Demand vector, *f*

	Flows	Demand vector, *f*
1	PS, (kg)	0
2	PVC, (kg)	0
3	PE, (kg)	0
4	Electricity, (kWh)	0
5	TV set, (No)	0
6	Provision of colour TV sets, (years)	f_u
7	Plastics collected for incineration, (kg)	0
8	Plastics collected for separation, (kg)	0

Technological Matrix, *A*

Flow					Vector process - p		
	1	2	3	4	5	6	7	8
	Production of PS (1 kg)	Production of PVC (1 kg)	Production of PE (1 kg)	Production of electricity	Production of TV set	Use of TV set	Separation of plastics for mechanical recycling	Incineration of plastics for energy recovery
PS, (kg)	$a_{1,1}$	0	0	0	$-a_{1,5}$	0	$M_c\left(\frac{a_{1,5}}{a_{1,5}+a_{2,5}+a_{3,5}}\right)$	0
PVC, (kg)	0	$a_{2,2}$	0	0	$-a_{2,5}$	0	$M_c\left(\frac{a_{2,5}}{a_{1,5}+a_{2,5}+a_{3,5}}\right)$	0
PE, (kg)	0	0	$a_{3,3}$	0	$-a_{3,5}$	0	$M_c\left(\frac{a_{3,5}}{a_{1,5}+a_{2,5}+a_{3,5}}\right)$	0
Electricity, (kWh)	$-a_{4,1}$	$-a_{4,2}$	$-a_{4,3}$	$a_{4,4}$	$-a_{4,5}$	0	$-M_p \cdot e$	$1.16 \cdot 10^{-3}\left[c \cdot d(1-r)\frac{(a_{1,5} \cdot H_1 + a_{2,5} \cdot H_2 + a_{3,5} \cdot H_3)}{a_{5,5}}\right]$
TV set, (No)	0	0	0	0	$a_{5,5}$	- d	0	0
astics collected for separation, (kg)	0	0	0	0	0	$M_{in} = \frac{(a_{1,5} + a_{2,5} + a_{3,5}) \cdot d \cdot c}{a_{5,5}}$	$-\frac{(a_{1,5} + a_{2,5} + a_{3,5}) \cdot d \cdot c}{a_{5,5}}$	0
astics collected for incineration, (kg)	0	0	0	0	0	$\frac{(a_{1,5} + a_{2,5} + a_{3,5}) \cdot d \cdot (1-c)}{a_{5,5}}$	$\frac{(a_{1,5}+a_{2,5}+a_{3,5})c \cdot d(1-r)}{a_{5,5}}$	$-\frac{(a_{1,5}+a_{2,5}+a_{3,5})d(1-c\,r)}{a_{5,5}}$
rovision of TV sets, (years)	0	0	0	0	0	*1*	0	0


Specify the collection rate: c
Specify the "rate of recovery", i.e. the required recovery: r
Specify the "base recovery": r_b
Specify the "base recovery": d
Set number of stages: $N = 1$
Cumpute M : $M = (a_{1,5} + a_{2,5} + a_{3,5}) \cdot d$
Cumpute M_{in} : $M_{in} = M \cdot c$
Cumpute M_w : $M_w = M \cdot (1 - c)$
$r < r_b$
YES
NO
$M_c = M_{in} \cdot r$
$M_{mid} = M_{in} - M_c$
$M_r = M_{in}$
$M_e = M_w + M_{mid}$
$M_c = M_{in} \cdot r_b$
$M_r = M_{in}$
Calculate middlings:
$M_{mid} = M_{in} - M_c$
Number of stages: $N = 1$
Collected mass: M_c
Mass of middlings: M_{mid}
Processed Mass: M_r
Plastics to be incinerated: M_e
$M_c < M_{in} \cdot r$
YES
NO
$N = N + 1$
$M_c = M_c + M_{mid} \cdot r_b$
$M_{mid} = M_{in} - M_c$
$M_r = M_r + M_{mid}$
$M_e = M_w + M_{mid}$
Number of stages: N
Collected mass: M_c
Mass of middlings: M_{mid}
Processed Mass: M_r
Plastics to be incinerated: M_e

Structure of LCA model

After choosing the ***FINAL DEMAND*** of the product, the simplest ***UNIT PROCESS*** can be written as follows:

INPUT

(***product flow***) x (***scaling parameter***) = (***final demand***)

OUTPUT

(***environmental flow***) x (***scaling parameter***) = (***environmental intervention***)

Ref.: Leontief, 1970 (Winner of Nobel Prize in 1973)

Inventory data

Input (-) → Process → Output (+)

Technology matrix; ***A***

Final demand vector; ***f***

	Process 1…	… … …	…Process n		
liter of fuel	0	0	F1		0
kWh electricity	A2	B2	0		0
m3 of waste water	10	0	0		100
kg of CO_2 (emitted)	A6	B6	F6		?
kg of Fe	A7	B7	F7		

Technological parameters

Emission from the process

Environmental intervention matrix; ***B***

?

Inventory; ***g***

Linear programming

(Heijung et.al, 2002)

$$\begin{cases} (a_{11} \times s_1) + (a_{12} \times s_2) + \ldots\ldots + (a_{1j} \times s_j) = f_1 \\ (a_{21} \times s_1) + (a_{22} \times s_2) + \ldots\ldots + (a_{2j} \times s_j) = f_2 \\ \vdots \\ \vdots \\ (a_{i1} \times s_1) + (a_{i2} \times s_2) + \ldots\ldots + (a_{ij} \times s_j) = f_j \end{cases}$$

$$\begin{cases} (b_{11} \times s_1) + (b_{12} \times s_2) + \ldots\ldots + (b_{1j} \times s_j) = g_1 \\ (b_{21} \times s_1) + (b_{22} \times s_2) + \ldots\ldots + (b_{2j} \times s_j) = g_2 \\ \vdots \\ \vdots \\ (b_{k1} \times s_1) + (b_{k2} \times s_2) + \ldots\ldots + (b_{kj} \times s_j) = g_j \end{cases}$$

$$\Rightarrow \begin{cases} \forall i : \sum_j a_{ij} s_j = f_i \\ \forall k : \sum_j b_{kj} s_j = g_k \end{cases}$$

Product flow,	***a***
Scaling parameter,	***s***
Demand,	***f***
Environmental flow ,	***b***
Environmental intervention ,	***g***

Equations can be written in terms of matrixes

$$
\begin{cases}
\begin{pmatrix}
a_{11} & a_{12} & \cdots & \cdots & a_{1j} \\
a_{21} & a_{22} & \cdots & \cdots & a_{2j} \\
\vdots & & \ddots & & \vdots \\
\vdots & & & \ddots & \vdots \\
a_{i1} & a_{i2} & \cdots & \cdots & a_{ij}
\end{pmatrix}
\times
\begin{pmatrix}
s_1 \\ s_2 \\ \vdots \\ \vdots \\ s_j
\end{pmatrix}
=
\begin{pmatrix}
f_1 \\ f_2 \\ \vdots \\ \vdots \\ f_j
\end{pmatrix}
\\
\begin{pmatrix}
b_{11} & b_{12} & \cdots & \cdots & b_{1j} \\
b_{21} & b_{22} & \cdots & \cdots & b_{2j} \\
\vdots & & \ddots & & \vdots \\
\vdots & & & \ddots & \vdots \\
\vdots & & & & \vdots \\
b_{k1} & b_{k2} & \cdots & \cdots & b_{kj}
\end{pmatrix}
\times
\begin{pmatrix}
s_1 \\ s_2 \\ \vdots \\ \vdots \\ s_j
\end{pmatrix}
=
\begin{pmatrix}
g_1 \\ g_2 \\ \vdots \\ \vdots \\ \vdots \\ g_k
\end{pmatrix}
\end{cases}
$$

Technology matrix

$$A = \begin{pmatrix} a_{11} & a_{12} & \cdots & \cdots & a_{1j} \\ a_{21} & a_{22} & \cdots & \cdots & a_{2j} \\ \vdots & & \ddots & & \vdots \\ \vdots & & & \ddots & \vdots \\ a_{i1} & a_{i2} & \cdots & \cdots & a_{ij} \end{pmatrix}$$

Final demand vector

$$f = \begin{pmatrix} f_1 \\ f_2 \\ \vdots \\ \vdots \\ f_j \end{pmatrix}$$

Scaling vector

$$s = \begin{pmatrix} s_1 \\ s_2 \\ \vdots \\ \vdots \\ s_j \end{pmatrix}$$

Intervention matrix

$$B = \begin{pmatrix} b_{11} & b_{12} & \cdots & \cdots & b_{1j} \\ b_{21} & b_{22} & \cdots & \cdots & b_{2j} \\ \vdots & & \ddots & & \vdots \\ \vdots & & & \ddots & \vdots \\ b_{k1} & b_{k2} & \cdots & \cdots & b_{kj} \end{pmatrix}$$

Inventory vector

$$g = \begin{pmatrix} g_1 \\ g_2 \\ \vdots \\ \vdots \\ g_j \end{pmatrix}$$

Linear programming / Matrix manipulation

(Heijung et.al, 2002)

$$\begin{cases} [A]\times[s]=[f] \\ [B]\times[s]=[g] \end{cases} \Rightarrow \begin{cases} [s]=[A^{-1}]\times[f] \\ [g]=[B]\times[s] \end{cases}$$

Final demand vector

Inverse matrix of technology matrix A

Scaling vector

Inventory vector

Environmental intervention matrix

Solution:

$$[g]=[B]\times[A^{-1}]\times[f]$$

LCI Results – ***g*** vector

The outcome of the inventory analysis was the vector *g*, which is a list of the quantities g_i of pollutants released to the environment and the amount of energy and materials consumed during the life-cycle of plastics for TVs production (Matrix ***B***), i.e.:

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

Phase 3 of LCA: Impact assessment

The categories of the environmental problems:

a) Resource depletion/Abiotic depletion **ADP** (in kg Sb eq.)
b) Global warming – **GWP** (in kg CO_2 eq.)
c) Acidification, **AP** (in kg SO_2 eq./kg)
d) Photo-oxidant formation, **POCP** (in kg C_2H_4 eq./kg)
e) Eutrophication, **EP** (in kg PO_4 eq./kg)
f) Human toxicity, **HTP** (in kg 1,4-DCB eq./kg)

How to calculate the environmental impact?

The impact indicator I_j of each category was calculated after all the environmental loads g_i within a category were characterized and aggregated using the following equations,

Results of LCI, ***g*** vector

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

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

Characterization factors, $k_{i(j)}$

	Flow	Impact indicators					
		ADP, (kg Sb eq./kg)	GWP, (kg CO_2 eq./kg)	AP, (kg SO_2 eq./kg)	POCP, (kg C_2H_4 eq./kg)	EP, (kg PO_4 eq./kg)	HTP, (kg 1,4-DCB eq./kg)
Resources							
$_{3}$	Naphtha	0.0201	-	-	-	-	-
$_{4}$	LPG	0.0187	-	-	-	-	-
$_{5}$	NGL	0.0187	-	-	-	-	-
$_{7}$	Coal	0.0067	-	-	-	-	-
$_{8}$	Natural gas	0.0187	-	-	-	-	-
$_{9}$	Petroleum	0.0201	-	-	-	-	-
$_{10}$	Crude oil	0.0201	-	-	-	-	-
$_{11}$	LNG	0.0187	-	-	-	-	-
Emission to air							
$_{12}$	CO_2	-	1	-	-	-	-
$_{13}$	CH_4	-	21	-	-	-	-
$_{14}$	HCF	-	2800	-	-	-	-
$_{15}$	N_2O	-	310	-	-	-	-
$_{16}$	SF_6	-	23900	-	-	-	-
$_{17}$	NO_x	-	-	0.7	0.028	0.130	1.2
$_{18}$	SO_x	-	-	1	0.048	-	0.096
$_{19}$	Dust	-	-	-	-	-	0.82
$_{20}$	HCl	-	-	0.88	-	-	0.5
$_{21}$	CO	-	-	-	0.027	-	-
Emission to water							
$_{22}$	COD	-	-	-	-	0.022	-
$_{23}$	T-P	-	-	-	-	3.060	-
$_{24}$	T-Ni	-	-	-	-	-	750
$_{25}$	Phenol	-	-	-	-	-	0.00008

Source: Handbook of LCA, 2002

Normalization

The indicator I_j of each environmental impact category is divided by a reference value known as normalization factor w_j

$$I_{j(w)} = \frac{I_j}{w_j} \quad , \quad j = 1,2,\ldots,q$$

q indicates the number of the environmental impact categories.

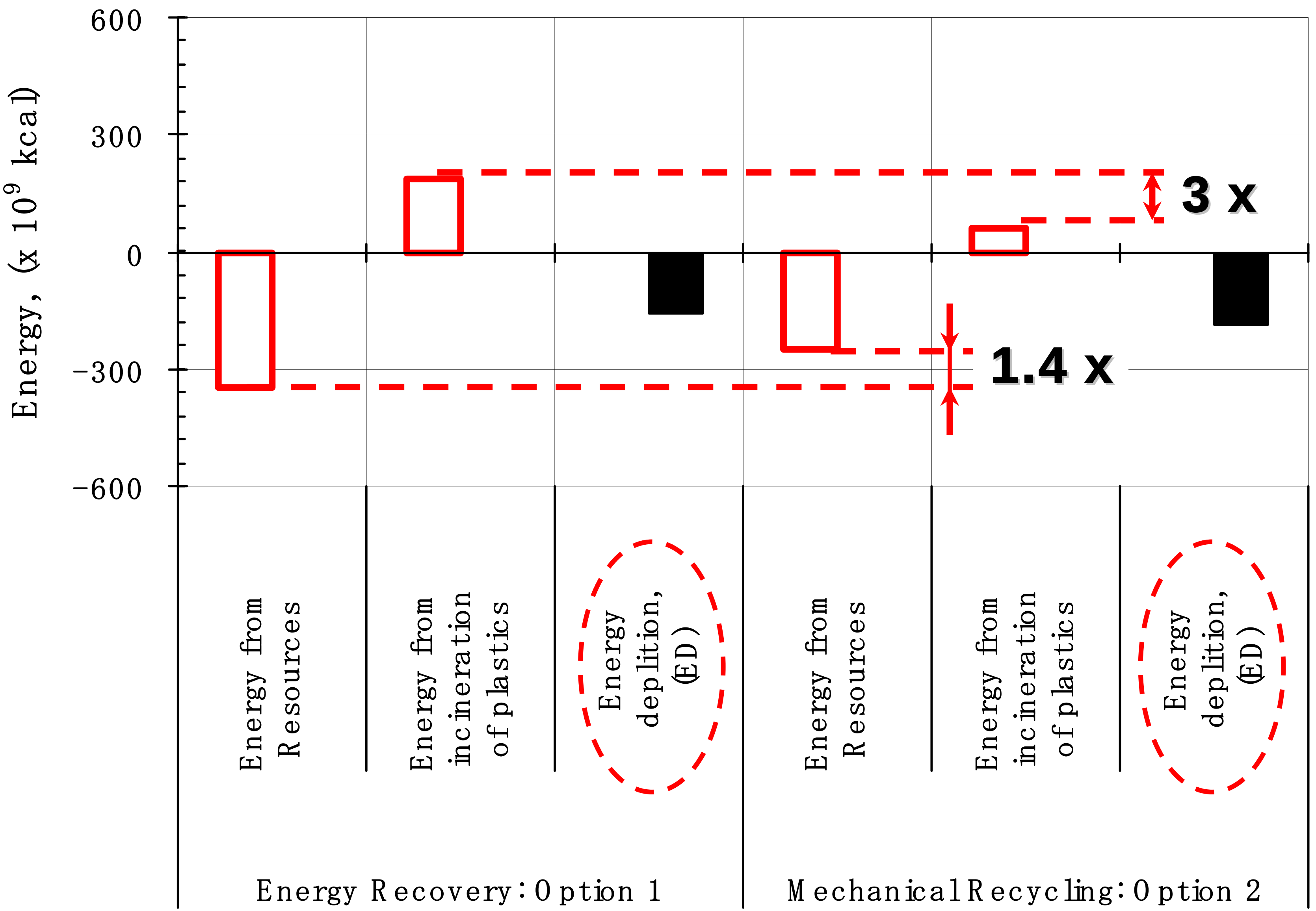
Weighting factors, k_i

Source: Handbook of LCA, 2002

World (1995)

ADP	$1.57 \cdot 10^{11}$	kg (Sb eq.) • yr^{-1}
GWP	$3.86 \cdot 10^{13}$	kg (CO_2 eq.) • yr^{-1}
AP	$2.99 \cdot 10^{11}$	kg (SO_2 eq.) • yr^{-1}
POCP	$4.55 \cdot 10^{10}$	kg (C_2H_4 eq.) • yr^{-1}
EP	$1.29 \cdot 10^{11}$	kg (PO_4 eq.) • yr^{-1}
HTP	$4.98 \cdot 10^{13}$	kg (1,4-DCB eq.) • yr^{-1}

Phase 3 of LCA: Impact assessment
a) Energy Depletion (ED)



Comparing **energy recovery** (option 1) with **mechanical recycling** (option 2)

Environmental Indicators	**Option 1, (Energy recovery)**	**Option 2, (Mechanical recycling)**
Energy balance (*ED*), in [kcal]	**-158,808,456,261**	**-186,049,047,033**
Abiotic depletion potential (*ADP*), in [kg Sb. eq.]	**1,143,091**	**698,156**
Global warming potential (*GWP*), in [kg CO_2 eq.]	**452,329,521**	**334,977,313**

An Estimate for the Environmental Burden (EEB)

$$EEB_{(c,r)} = \sum_{j=1}^{q} I_{j(w)} \quad , \quad c = 0...100\% \quad , \quad r = 0...100\%$$

3.4.3. Sensitivity Analysis - *perturbation method*

(Matrix of Environmental Load, *g*)

$$S_{(i)} = \frac{\partial g_{(k)}}{\partial A} = E^T e_k s^T \otimes A$$

where: $E = -g_{diag} B \cdot A^{-1}$

$$g_{diag} = \begin{bmatrix} 1/g_1 & \cdots & \cdots & \cdots & 0 \\ \vdots & \ddots & & & \vdots \\ \vdots & & \ddots & & \vdots \\ \vdots & & & \ddots & \vdots \\ 0 & \cdots & \cdots & \cdots & 1/g_s \end{bmatrix}$$

$$e_k = \begin{bmatrix} e_1 \\ \vdots \\ e_i \\ \vdots \\ e_n \end{bmatrix} , \qquad e_i = \begin{cases} 1 & \text{if} \quad i = k \\ 0 & \text{otherwise} \end{cases}$$

$$l_{i(\alpha,\beta)} = s_{i(\alpha,\beta)} \cdot \max\left(\frac{k_{i(j)}}{w_j}\right) , \; i = 1,2,\ldots n \; , \; \alpha = 1,2,\ldots m \; , \; \beta = 1,2,\ldots p \; , \; j = 1,2,\ldots q$$

Sensitivity Analysis

Scenarios for:

a. **saving resources** (ADP), and

b. **reducing the greenhouse gas emission** (GWP)

Element	Process	Entity	Load	Category	Sensitivity	Scenario
a56	Use of TV sets	TV sets	Naphta (g3)	ADP	1.2744	Decrease demand
a66	Use of TV sets	Collected PLASTICS for separatio	Naphta (g3)	ADP	-0.8941	Increase the collection rate of Plastic waste
a15	Production of TV sets	PS (kg)	Naphta (g3)	ADP	0.8902	Decrease the amount of PS Use for TV
a17	Recovery of plastics	PS (kg)	Naphta (g3)	ADP	-0.6239	**Improve RECOVERY of PS**
a86	Use of TV sets	Use (year)	CO2 (g14)	GWP	-0.4709	Increace LIFE of a TV sets, i.e. production process
a56	Use of TV sets	TV sets	CO2 (g14)	GWP	0.4285	Decrease demand
a11	Production of PS	PS (kg)	Naphta (g3)	ADP	-0.2701	Improve the efficiency of the process for production of PS
a25	Production of TV sets	PVC (kg)	Naphta (g3)	ADP	0.2359	Decrease the amount of PVC use for TV
a27	Recovery of plastics	PVC (kg)	Naphta (g3)	ADP	-0.1636	Improve RECOVERY of PVC
a35	Production of TV sets	PE (kg)	Naphta (g3)	ADP	0.1484	**Decrease the amount of PE Use for TV**
a37	Recovery of plastics	PE (kg)	Naphta (g3)	ADP	-0.1103	Improve RECOVERY of PE
a22	Production of PVC	PVC (kg)	Naphta (g3)	ADP	-0.0723	Improve the efficiency of the process for production of PVC
a33	Production of PE	PE (kg)	Naphta (g3)	ADP	-0.0381	Improve the efficiency of the process for production of PE
a35	Production of TV sets	PE (kg)	CH4 (g15)	GWP	0.0037	**Decrease the amount of PE Use for TV**
a35	Production of TV sets	PE (kg)	CO2 (g14)	GWP	0.0331	**Decrease the amount of PE Use for TV**
a35	Production of TV sets	PE (kg)	N20 (g17)	GWP	0.0021	**Decrease the amount of PE Use for TV**

3.4.4. Strategy to reduce the environmental burden

1. Collect as many TV sets as possible
2. Use **PS** instead of PVC or **PE** for production of TV sets (i.e. possibly excluding PVC)

in turn:

a. The efficiency of the separation process will be improved reducing the ADP indicator,

b. The emission of CH_4 and CO_2 will be reduced (i.e. GWP)