M2794.006900 DESIGN FOR MANUFACTURING

Week 11, November 14

Life Cycle Assessment (LCA)

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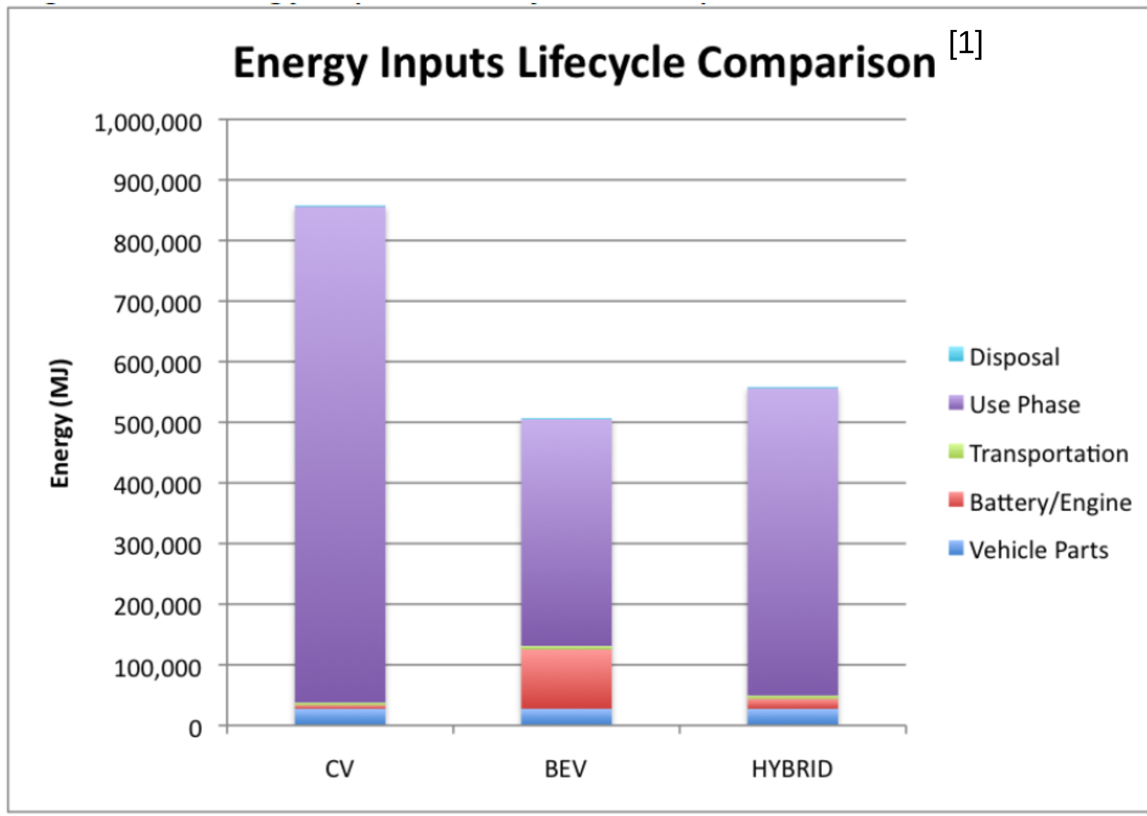
Example of LCA - CAR



CV - conventional gasoline vehicle
BEV - battery electric vehicle
HYBRID - hybrid vehicle

[1] Deepak R. *et al.*, Lifecycle Analysis Comparison of a Battery Electric Vehicle and a Conventional Gasoline Vehicle, 2012

LCA - CAR

2013 Gas, Electric & Hybrid car comparison

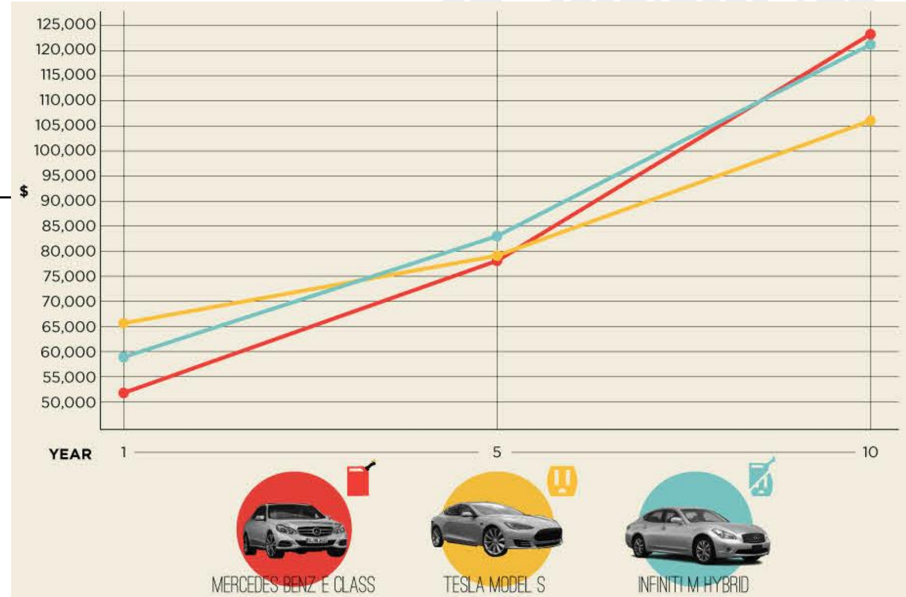
Luxury cars

NAME OF CAR	ENGINE TYPE	PRICE	MPG	RANGE	REFUEL TIME
MERCEDES BENZ E CLASS	gas	$51,000	City: 20 Hwy: 30	437 miles on a full tank	Minutes at a gas station
TESLA MODEL S	electric	$69,900	City: 94 Hwy: 97	208 miles on a full charge	10 hours at 240 volts
INFINITI M HYBRID	hybrid	$54,750	City: 27 Hwy: 32	465 miles on a full tank	Minutes at a gas station

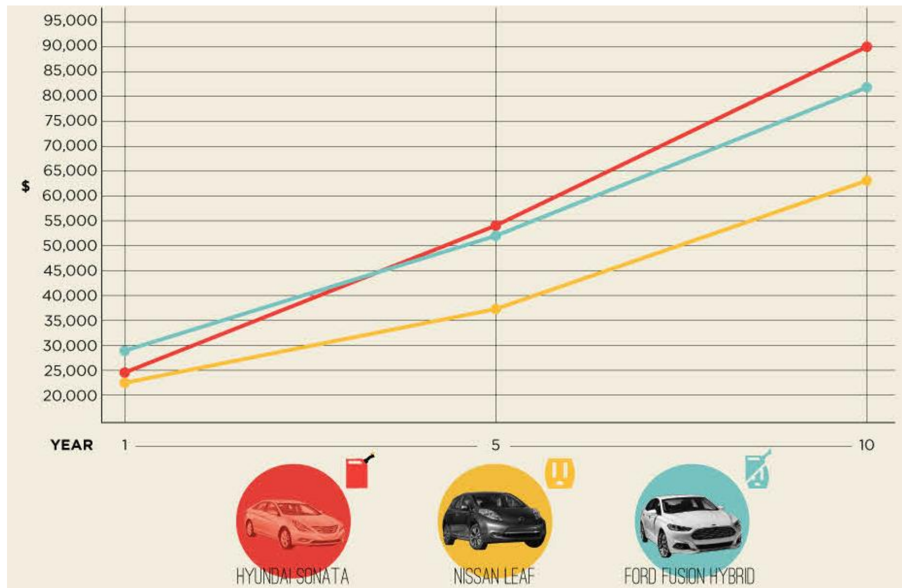
Affordable midsize cars

NAME OF CAR	ENGINE TYPE	PRICE	MPG	RANGE	REFUEL TIME
HYUNDAI SONATA	gas	$20,895-$27,595	City: 24 Hwy: 35	466 miles on a full tank	Minutes at a gas station
NISSAN LEAF	electric	$28,800-$34,840	City: 129 Hwy: 102	75 miles on a full charge	7 hours at 240 volts
FORD FUSION HYBRID	hybrid	$27,200-$32,100	City: 47 Hwy: 47	571 miles on a full tank	Minutes at a gas station

Mpg (mile per gram)



Price for car + annual operating costs (Luxury cars)

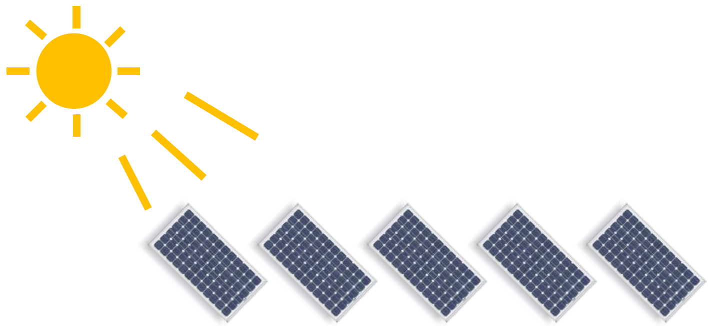


Price for car + annual operating costs (Affordable midsize cars)

Ref. Nowsourcing, 2013

LCA in Solar Power Generation System

- Calculate and select efficient system using LCA



Power Generation: Solar Panel

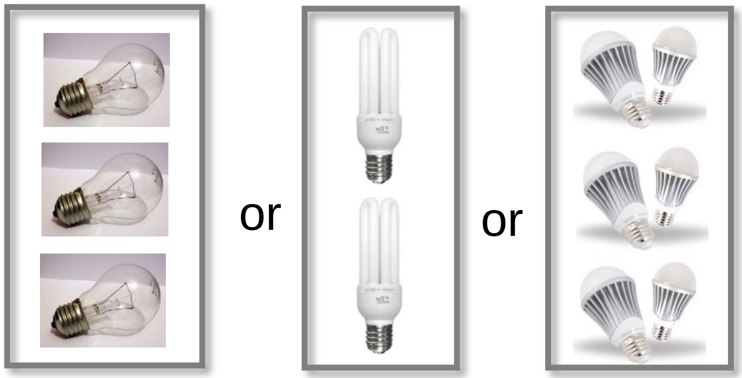
In daytime
(5 hr)

Quiz :
Select the most efficient system among the different kind of light bulbs after 25 year.

In night time
(6 hr)

Energy Storage: Battery

Required total number of bulbs: 100



Power Consumption: Light Bulb

Power Consumption Components (Light Bulb)

- LED
  - Price: 8 USD
  - Life time: 15 years
  - Power : 7.2 W
  - 650-700 Lumens

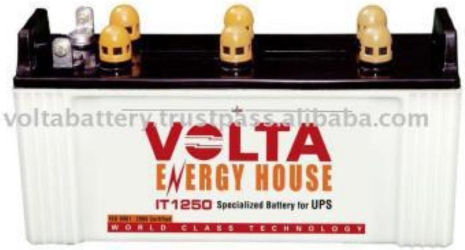
- Fluorescent Lamp
  - Price: 4 USD
  - Life time : 5 years
  - Power : 14 W
  - 700 Lumens

- Incandescent Lamp
  - Price: 1 USD
  - Life time: 1 year
  - Power: 60 W
  - 700 Lumens

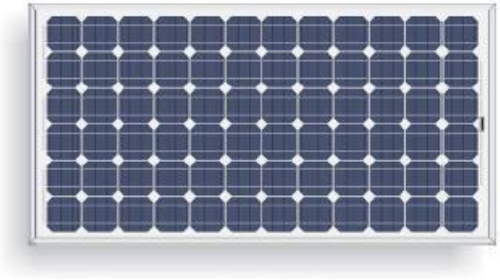
(The power of each bulb is set to have same brightness)

Maintenance Components

- Battery
  - Price: 380 USD
  - Life time: 5 years
  - Capacity : (12 V, 140 Ahr)



- Solar Panel
  - Price: 162 USD
  - Generation capacity: 120 W/hr
  - Life time: 20 years



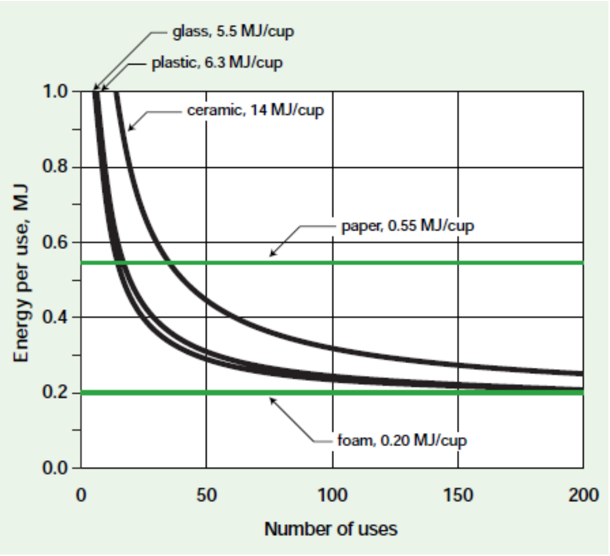
Hint : make the plot of Time vs. Cost

Basic DFE methods: design guidelines

VS

Paper cup

Mug cup



	Paper Cups (2 Per Day X 7 Billion X 365)	Ceramic Cups
Total Cups	5.1 Trillion	7 Billion
Embodied Energy	2.8 Trillion MJ	98 Billion MJ
Energy per year to wash	N/A	919 Billion MJ
Total Energy	**2.8 Trillion MJ**	**1.01 Trillion MJ**
Water to produce	2.5 Trillion L	N/A
Water per year to wash	N/A	2.7 Trillion L
Total water	**2.5 Trillion L**	**2.7 Trillion L**

Ref. Institute for lifecycle energy analysis

Basic DFE methods: design guidelines

- Product Design (Otto)
- Simple and effective when implemented
- Consult the guideline for each developed concept and after embodiment of the concept

TABLE 15.1. PRODUCT STRUCTURE GUIDELINES

Guideline	Reason
Design a product to be multifunctional.	More ecoefficient than many unique-function products.
Minimize the number of parts. Create multifunctional parts.	Reduces disassembly time and resources.
Avoid separate springs, pulleys, or harnesses. Instead, embed these functions into parts.	Reduces disassembly time and resources.
Make designs as modular as possible, with separation of functions.	Allows options of service, upgrade, or recycling.
Design a reusable platform and reusable modules.	Allows options of service, upgrade, or recycling.
Locate unrecyclable parts in one subsystem that can be quickly removed.	Speeds disassembly.
Locate parts with the highest value in easily accessible places, with an optimized removal direction.	Enables partial disassembly for optimum return.
Design parts for stability during disassembly.	Manual disassembly is faster with a firm working base.
In plastic parts, avoid embedded metal inserts or reinforcements.	Creates the need for shredding and separation.
Access and break points should be made obvious.	Logical structure speeds disassembly and training.
Specify remanufactured parts.	Stimulate demand for remanufacturing, reducing raw material consumption.
Specify reusable containers for shipping or consumables within the product.	Reduces raw material consumption.
Design power-down features for different subsystems in a product when they are not in use.	Eliminate unnecessary power consumption for idle components.
Lump individual parts with the same material.	Eliminates the need for disassembly during recycling. Neighbor parts may be ground or melted as a group.

TABLE 15.2. MATERIAL SELECTION GUIDELINES

Guideline	Reason
Avoid regulated and restricted materials.	They are high impact.
Minimize the number of different types of material.	Simplifies the recycling process.
For attached parts, standardize on the same or a compatible material. Eliminate incompatible materials.	Reduces the need for disassembly and sorting.
Mark the material on all parts.	Many materials' value is increased by accurate identification and sorting.
Use recycled materials.	Stimulate the market for material that has been recycled.
Use materials that can be recycled, typically ones as pure as possible (no additives).	Minimize waste; increase the end-of-life value of the product.
Avoid composite materials.	Composites are inherently not pure materials, and so not amenable to recycling.
Use high strength-to-weight materials on moving parts.	Reduce moving mass and therefore energy consumption.
Use low-alloy metals that are more recyclable than high-alloy ones.	More pure metals can be recycled into more-varied applications.
If the same base metal can be used, different metals can be fastened.	Aluminum, steel, and magnesium alloys are readily separated from shredder output and recycled.
Hazardous parts should be clearly marked and easily removed.	Rapidly eliminate parts of negative value.

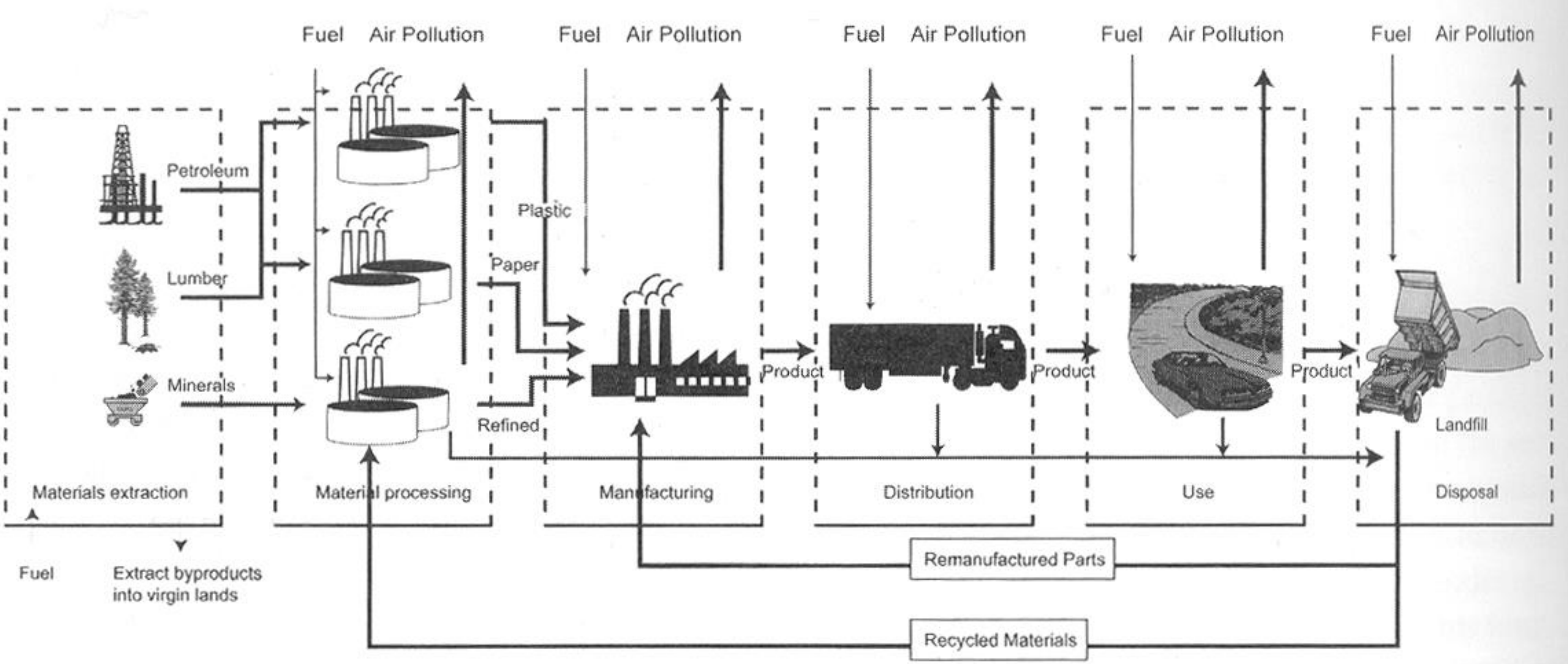
TABLE 15.3. LABELING AND FINISH GUIDELINE

Guideline	Reason
Ensure compatibility of ink where printing is required on parts.	Maintain maximum value of recovered material.
Eliminate incompatible paints on parts—use label imprints or even inserts.	Many label-removal operations for paints cause part deterioration.
Use unplated metals that are more recyclable than plated.	Some plating can eliminate recyclability.
Use electronic part documentation.	These parts can be reused.

TABLE 15.4. FASTENING GUIDELINES

Guideline	Reason
Minimize the number of fasteners.	Most disassembly time is fastener removal.
Minimize the number of fastener removal tools needed.	Tool changing costs time.
Fasteners should be easy to remove.	Save time in disassembly.
Fastening points should be easy to access.	Awkward movements slow down manual disassembly.
Snap fits should be obviously located and able to be torn apart using standard tools.	Special tools may not be identified or available.
Try to use fasteners of material compatible with the parts connected.	Enables disassembly operations to be avoided.
If two parts cannot be compatible, make them easy to separate.	They must be separated to recycle.
Eliminate adhesives unless compatible with both parts joined.	Many adhesives cause complete contamination of parts for material recycling.
Minimize the number and length of interconnecting wires or cables used.	Flexible elements slow to remove; copper contaminates steel, etc.
Connections can be designed to break as an alternative to removing fasteners.	Fracture is a fast disassembly operation.

Life Cycle Assessment (LCA)



▼ ***Figure 15.9.***
Typical material and energy flows over a product life cycle.

More systematic analysis of a product

Example of cost parameters

Table 2 Evaluation of two alternatives with cost parameters.

Parameter	*Alternative A*	*Alternative B*
General information		
Car type	Car type A, new, with a small and efficient motor	Care type B, five years old, low investment
Weight	1450 kg	1750 kg
Functionality	5 seats, ABS	7 seats, 4 wheel drive
General cost		
Investment	25 000 €	12 000 €
Cost for product use		
Driving distance per year	20 000 km/year	20 000 km/year
Liter gasoline/100 km	6 L/100 km	10 L/100 km
Gasoline consumption over 5 years	6000 liter	10 000 liter
Fuel and oil cost (over 5 years)	6000 €	10 000 €
Insurance (over 5 years)	6000 €	8000 €
Tax (over 5 years)	5000 €	6000 €
Repair (over 5 years)	2000 €	8000 €
Cost concerning end of life		
Value after 5 years	12 000 €	2000 €
Total costs over 5 years	32 000 €	42 000 €
Costs per 1 km	0.32 €/km	0.42 €/km

Kyoto Protocol

- The **Kyoto Protocol** is a protocol to the United Nations Framework Convention on Climate Change (UNFCCC or FCCC), aimed at fighting global warming.

Kyoto Protocol participation map as of February, 2012
Green indicates countries that have ratified the treaty
(Annex I & II countries in **dark green**)
Brown = No intention to ratify
Red = Countries which have withdrawn from the Protocol.
Grey = no position taken or position unknown

Kyoto Protocol

- **The five principal concepts**
  - Commitments for the Annex I Parties.

    (Reduction of greenhouse gases that are legally binding for Annex I Parties).
  - Implementation. In order to meet the objectives of the Protocol, Annex I Parties are required to prepare policies and measures for the reduction of greenhouse gases in their respective countries.
  - Minimizing Impacts on Developing Countries by establishing an adaptation fund for climate change.
  - Accounting, Reporting and Review in order to ensure the integrity of the Protocol.
  - Compliance. Establishing a Compliance Committee to enforce compliance with the commitments under the Protocol.

Carbon footprint

- **Carbon footprint** has historically been defined as "the total set of greenhouse gas (GHG) emissions caused by an organization, event, product or person.

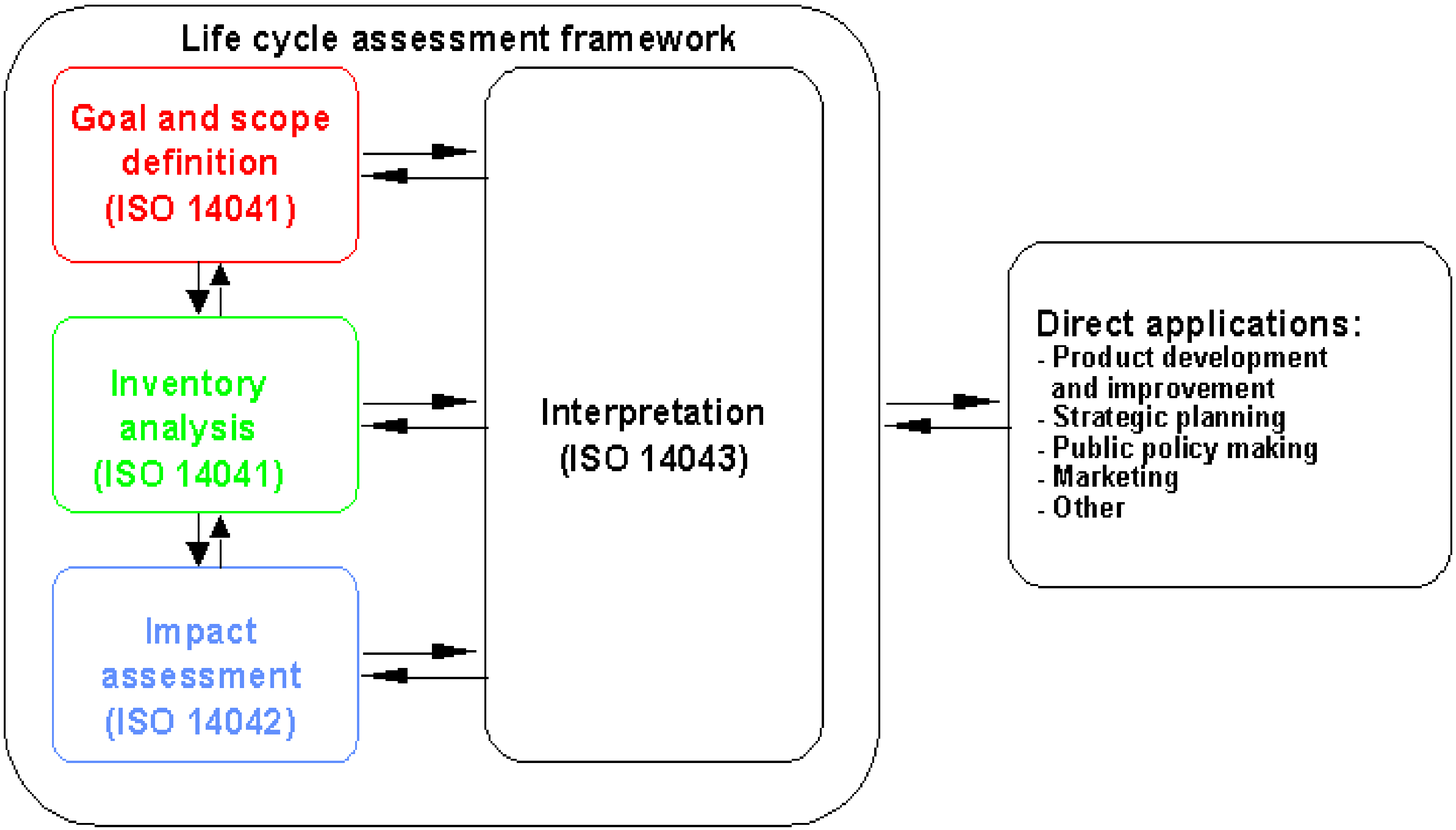
- Carbon footprint originates from ecological footprint (developed by Rees and Wackernagel in the 1990s)

- Carbon footprint can be measured by undertaking a GHG emissions assessment

- The mitigation of carbon footprints through the development of alternative projects (solar or wind energy or reforestation) represents one way of reducing a carbon footprint. Carbon offsetting.

General principle of LCA

ISO 14040



1. Goal & scope definitions phase

- Goal definition
  - Why perform LCA?
  - Who are the target audiences?
  - What is the application of the LCA results?
- Scope definition
  - Defining product system and setting its boundary
  - Defining product function and its unit
  - Setting data quality requirements and data parameters

Example of crude oil

- Simple product

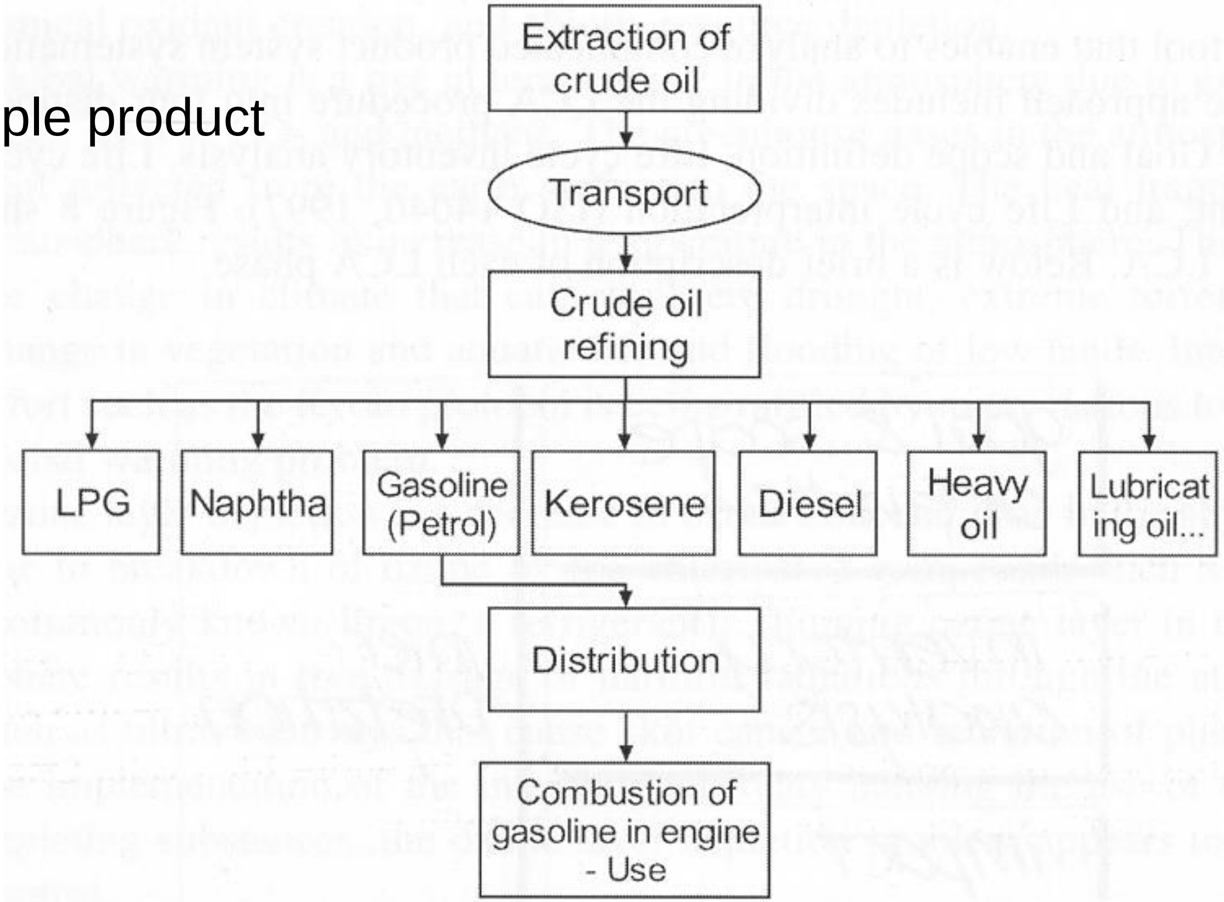


Figure 9 Product system of the fuel (gasoline).

2. Inventory analysis phase

- Data collection for input and output

Table 7 Examples of data category and parameter.

Category	*Parameter*
Emissions to air	CO_2, CH_4
Emissions to water	Phenol, Phosphate, Nitrate
Emissions to land	Solid waste
Resources	Iron ore, Crude oil

Table 8 Example of inventory analysis results of 1 kg fuel (unit: g/kg fuel).

Inventory parameter	*Use of raw materials*	*Manufacture*	*Distribution*	*Product use*	*Total*
Crude oil	1173.00	0.00	0.00	0.00	1173.00
CO_2	336.72	449.28	27.20	1880.50	2693.70
CH_4	4.69	0.07	0.05	0.00	4.81
NO_x	1.74	0.97	0.25	1.55	4.51

3. Impact assessment phase

- Mandatory elements –classification and characterization
- Optional element – normalization and weighting

Table 9 Example of classification of the fuel: linking between inventory parameter and impact category.

Inventory parameter	*Impact category*
CO_2	GW
CH_4	GW, POC
NO_x	AD, EU, POC
Crude oil	ARD

Table 10 Characterized impact of the fuel (for global warming impact category).

Inventory parameter	*Load (g/kg fuel)*	*Factor (g CO_2 eq/g)*	*Characterized impact (g CO_2 eq/kg fuel)*
CO_2	2693.70	1	2693.70
CH_4	4.81	23	110.63
Total			2804.33

↑ Equivalency factor

4. Interpretation phase

Table 11 Life cycle interpretation results (key issue identification) of the fuel (for global warming impact category) (unit: g CO_2 eq/fu).

Inventory parameter	*Use of raw materials*	*Manufacture*	*Distribution*	*Product use*	*Total*
CO_2	336.72	449.28	27.20	1880.50	2693.70
CH_4	107.87	1.61	1.15	0.00	110.63
Total	444.59	450.89	28.35	1880.50	2804.33
	16%	16%	1%	67%	100%

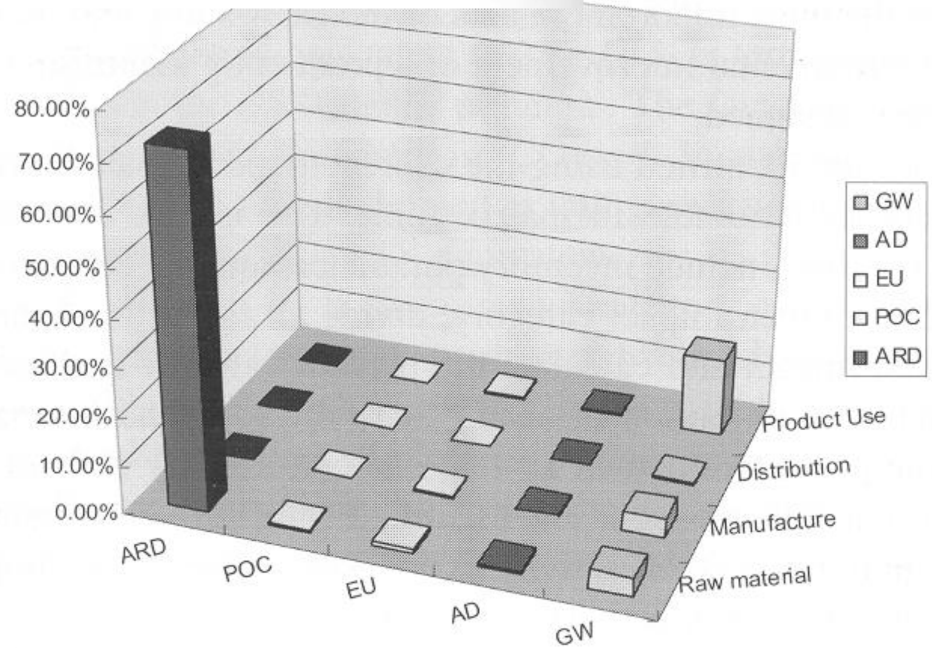


Figure 10 Key issues identified for the fuel based on weighted impact.

Case study of water kettle

Table 6 Environmental parameters with quantified information including other realistic scenarios and additional information of the water kettle.

Environmental parameters – general information	
Name of the product	Water kettle
Weight	Weight 0.87 kg (including packaging)
Volume	200 × 200 × 350 mm
Supply part's environmental performance	Heater and cable
Lifetime	3 years
Functionality	Heating and boiling water with automatic switch off
Environmental parameters – life cycle related information	
Use of raw material	
Materials used	410 g PP, 120 g steel, 20 g PA, 72 g PVC, 48 g Cu, 200 g cardboard
Problematic materials	PVC in cables
Manufacture	
Production technology	Injection molding (housing: 330 g PP; lid: 80 g PP; switch unit: 20 g PA) Cutting and bending (120 g steel) Extrusion (72 g PVC) Stranded cable (48 g Cu) Cutting and gluing of box (200 g cardboard)
Production waste	None

Case study of water kettle (2)

Distribution	
Packaging	Single use cardboard box
Transportation	3000 km by 40 ton truck
Product use	
Usability	No flexibility in moving the kettle due to fixed cable
Energy consumption	Boiling 0.5 liter water requires 0.0545 kWh, for 2250 uses this equals 122.6 kWh
Waste (generated)	None
Noise and vibrations	None
Emissions	None
Maintenance	To clean the water kettle especially from calcium deposit (descaling)
Reparability	Not possible
End of life	
Fasteners and joints	Snap fit and screws
Time for disassembly	Disassembly is not possible
Rate of reusability	Reuse of parts is not possible
Rate of recyclability	50% of the total weight of the product
Information about other realistic scenarios	
Re-boil (product use)	The energy consumption per use can be about 20% higher: this can occur with a probability of about 50%

Case study of water kettle (3)

Table 6 (Continued)

Warm-up too much water (product use)	The energy consumption per use can be about 100% higher: this can occur with a probability of about 25%
Additional information	
Business case	Selling water kettles on the European market; no additional service and maintenance is provided
Current sales per year	91 800 (reference year is 2003)

LCA in detail

- Case study of a water kettle
- Product composition

Table 12 Product composition of a water kettle.

Component	*Material*	*Weight (g)*	*Weight (%)*
Housing	PP	330.00	38
Packaging	Card board	200.00	23
Heater	Stainless steel	120.00	14
Lid	PP	80.00	9
Cable (PVC)	PVC	72.00	8
Cable (Cu)	Cu	48.00	6
Switch unit	PA	20.00	2
Total		870.00	100

Life cycle data

Table 13 Life cycle data of a water kettle.

Life cycle stage	*Description*	*Data*
Use of raw materials	See Table 12	See Table 12
Manufacture (including components manufacturing)	Electricity was the only input to the manufacturing of components and assembly of water kettle.	Electricity consumption for the manufacturing of housing, packaging and heater was 0.5, 0.2 and 1.5 kWh, respectively. There are two types of product assembled, model A and model B. Production volume of model A and B is 7650 and 8900 units/month, respectively. Total electricity consumed in manufacturing (assembling) of both models was 10 000 kWh per month.
Distribution	The distribution is done within Europe by 40-ton trucks.	The average distance for transport is 3000 km.
Product use	Use scenario: heating ½ liter of water to prepare tea or coffee in an office, 3 times a day, 5 days a week, 50 weeks a year. The total uses add up to 2250 times over the 3 year lifetime of the product.	Electricity consumed is 0.0545 kWh per use.
End of life	Disposal via municipal waste route.	The ratio of recycling, incineration, and landfill is 50%, 20%, and 30%, respectively.

1. Goal and scope definition

- Goal definition
  - Why: to generate environmental profile data and to identify key issues of the water kettle
  - Who: product designers, developers, and managers within the company, and retail and institutional level consumers as well as B2B consumers in the supply chain
  - What: redesign of the reference product

1. Goal and scope definition (2)

- Scope definition
  - Function
  - System boundary
    - Table 14, figure 11

Table 14 Components of the water kettle included in the product system (marked in bold).

Component	*Material*	*Weight (g)*	*Weight percent (%)*	*Cumulative weight percent (%)*
Housing	**PP**	**330.00**	**38**	**38**
Packaging	**Card board**	**200.00**	**23**	**61**
Heater	**Stainless steel**	**120.00**	**14**	**75**
Lid	PP	80.00	9	84
Cable (PVC)	PVC	72.00	8	92
Cable (Cu)	Cu	48.00	6	98
Switch unit	PA	20.00	2	100
Total		870.00	100	

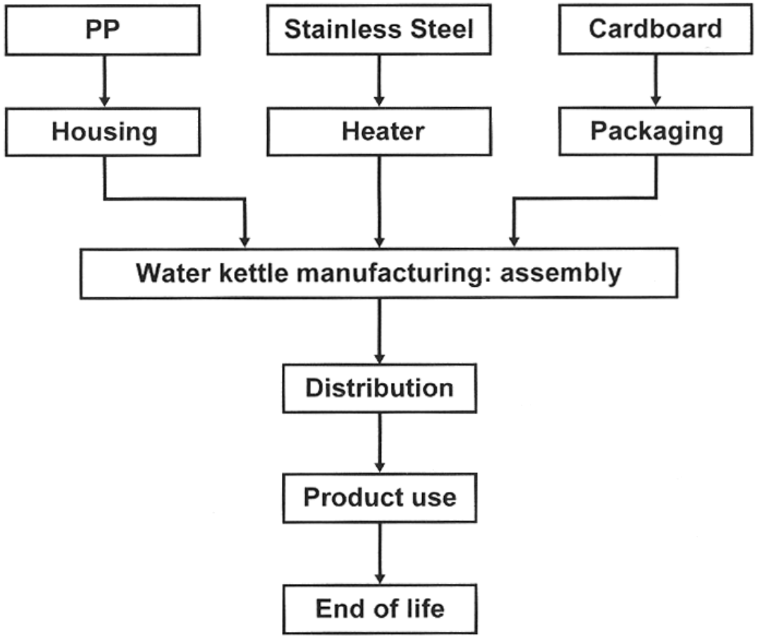


Figure 11 Process tree of the water kettle.

1. Goal and scope definition (3)

- Data category

Table 15 Data category and parameters.

Broader data category	*Specific data category*	*Parameters (illustrative)*
Input	Raw materials	Crude oil, Iron ore
	Ancillary materials	Solvent, Process materials
	Energy	Electricity, LNG
Output	Products	Water kettle
	Co- and/or by-products	Slag
	Emissions to air	CO_2, Methane
	Emissions to water	Phenol; Organic carbon
	Emissions to land	Solid waste, Heavy metals

2. Life cycle inventory analysis

- Data collection
  - Preparing for data collection
  - Data questionnaire format: table 16

Table 16 One possible form of data questionnaire format with illustrative data for a heater.

Product name: Heater		Contact details: Mr. John	
Manufacturer: Company			
Data collection period: from January 1, 2003 to December 31, 2003			
Manufacturing process information: it should include process schematic diagram			
Input data			
Raw and ancillary materials and energy used			
Parameter	*Unit*	*Quantity*	*Country of origin*
Stainless steel	kg	0.5	Korea
Transport			
Transport mode	*Distance traveled*		*Mass transported*
40 ton trailer truck	3000 km		20 ton
Output data			
Emissions to Air, Water, and Land			
Parameter	*Unit*		*Quantity*
CO_2	g/kg product		3650

2. Life cycle inventory analysis (2)

- Data collection

Table 17 Possible data sources for various data categories.

Input data	
Raw and ancillary materials, parts and components	Purchasing records, bill of materials, process schematic diagram, production records.
Energies	Source of electricity (where does the electricity come from?), amount of electricity, fuels and steam used.
Output data	
Emissions to air, water and land	Measured emission data, calculated emission data, legal discharge limits.
Products and co-/by-products	Amount of products, by-/co-products (unit or mass or volume) manufactured, unit product weight and wholesale price.

2. Life cycle inventory analysis (3)

- Data base

Table 18 Database for the water kettle LCA (simplified version).

	Parameter	*Category*	*Unit*	*Total*
PP (1 kg)	Crude oil	Raw	g	1200
	CO_2	Air	g	1800
	NO_x (as NO_2)	Air	g	10
	SO_x (as SO_2)	Air	g	11
	VOC	Air	g	9.60
Cardboard (1 kg)	Crude oil	Raw	g	114
	CO_2	Air	g	467
	NO_x	Air	g	3.96
Stainless steel (1 kg)	Crude oil	Raw	g	294
	Coal	Raw	g	779
	Chromium	Raw	g	203
	Iron ore	Raw	g	655
	CO_2	Air	g	3650
Electricity (1 kWh)	Coal	Raw	g	50
	CO_2	Air	g	290
	Methane	Air	g	0.53
	SO_2	Air	g	1.18
Transport (40 t Truck, 1 ton-km, 50% loaded)	Crude oil	Raw	g	28
	CO	Air	g	0.51
	CO_2	Air	g	93
Incineration (1 kg waste)	Coal	Raw	g	0.16
	Crude oil	Raw	g	0.70
	CO_2	Air	g	3.56
	NO_x (as NO_2)	Air	g	0.13
Landfill (1 kg waste)	Crude oil	Raw	g	0.95
	CO_2	Air	g	19
	Methane	Air	g	1.97
	SO_x (as SO_2)	Air	g	0.03
Recycling (1 kg waste)	Coal	Raw	g	7.88
	Crude oil	Raw	g	–75
	Iron (ore)	Raw	g	–106
	CO_2	Air	g	–200

(Note: A negative value for the recycling means that there is an environmental benefit or positive environmental impact accrued from recycling, not adverse environmental impacts.)

2. Life cycle inventory analysis (4)

- Data computation

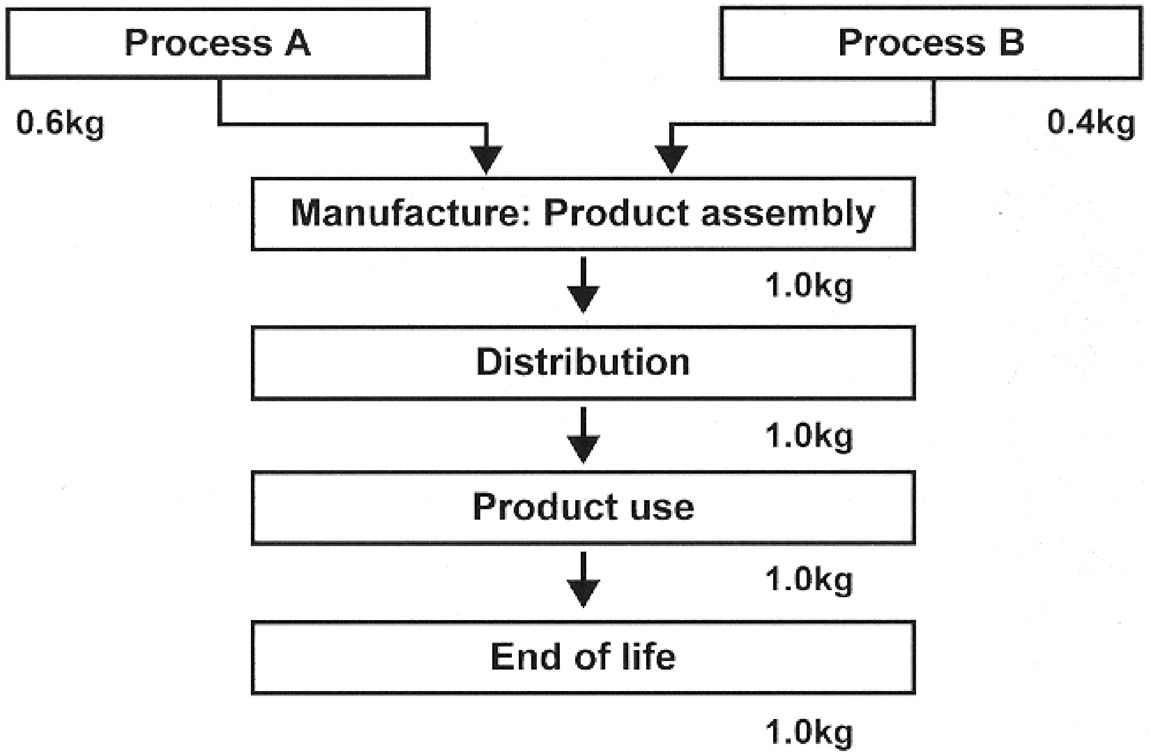


Figure 12 Process tree showing fictitious product system.

2. Life cycle inventory analysis (4)

- Data allocation

Table 19 Allocation factor based on economic value.

Type of model	*Unit produced (unit/month)*	*Sale price (Euro/piece)*	*Total sale price (Euro)*	*Allocation factor (%)*
Model A	7 650	18	137 700	38.2
Model B	8 900	25	222 500	61.8
Total	16 500	43	360 200	100.0

2. Life cycle inventory analysis (5)

- Special case of allocation: recycling

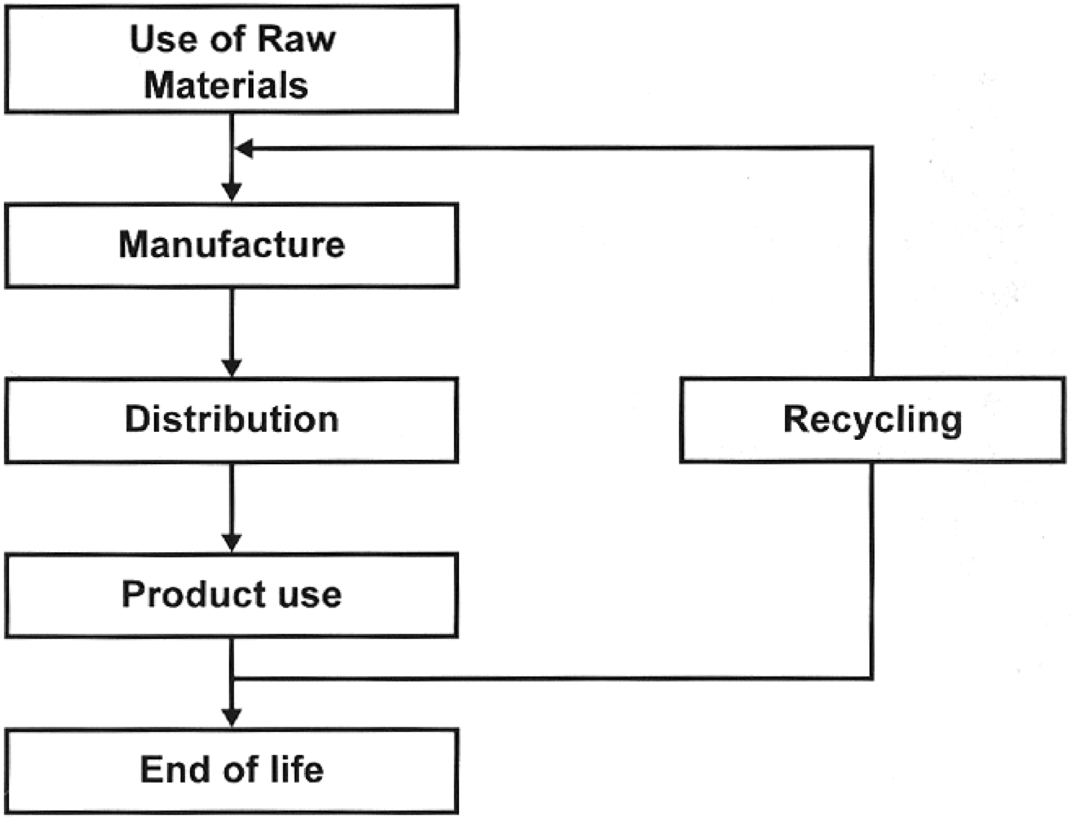


Figure 13 Simplified product system with waste recycling.

2. Life cycle inventory analysis (6)

- Allocation of environmental load

Table 20 Environmental load of each life cycle stage due to recycling.

Life cycle stage	*Allocation of EL due to recycling*	*EL with recycling (points/kg)*	*EL without recycling (points/kg)*
Use of raw materials	Net virgin material use = 300/kg × 0.4 kg = 120	120	300
End of life (disposal)	Waste disposed of = 200/kg × 0.4 kg = 80	80	200
End of life (Recycling)	Amount recycled = 100/kg × 0.6 kg = 60	60	0
Sum		260	500

2. Life cycle inventory analysis (7) : summary

- Process tree with material and fractional contribution: See Figure 11.
- The LCI database: see Table 18.
- Life cycle inventory data collection and calculation

I. Data from the use of raw materials stage (extraction of resources from nature to production of raw and ancillary materials)
   - Amount of raw material required for the three components
     PP for housing (w/handle) = 330 g
     Cardboard for packaging = 200 g
     Stainless steel for heater = 120 g
   - Calculation of the EL of the production of PP, cardboard, and stainless steel for the three components
     DB_{PP}/kg × 0.33 kg/housing
     $DB_{cardboard}$/kg × 0.2 kg/packaging
     $DB_{stainless\ steel}$/kg × 0.12 kg/heater
   - Total EL from the use of raw materials stage
     Sum of the EL from the production of PP, cardboard, and stainless steel for housing, packaging and heater. Here, as we took the 75% decision rule for mass inclusion, we must adjust the data for the three components.
     Adjusted EL = actual EL × 1/decision rule for mass inclusion factor = (EL (PP) + EL (cardboard) + EL (stainless steel))/0.75

II. Data from manufacture stage (components manufacturing and water kettle assembly)

(Continued)

Electricity was the only energy input to the assembly of water kettle, and manufacturing of housing, packaging, and heater. In addition, there were no other outputs except the housing, packaging, and heater from each process. In other words, wastes and scraps were not generated during the manufacture stage. Clearly, this is an oversimplified case.
   - Calculation of electricity consumed and EL for Model A
     Electricity consumed for model A = 10 000 kWh/month × (0.38)/(7650 unit/month) = 0.5 kWh/water kettle
     EL of water kettle assembly = $DB_{electricity}$/kWh × 0.5 kWh/water kettle
   - Calculation of EL of the three components.
     Electricity consumed for housing = 0.5 kWh
     Electricity consumed for packaging = 0.2 kWh
     Electricity consumed for heater = 1.5 kWh
     EL of housing = $DB_{electricity}$/kWh × 0.5 kWh/housing
     EL of packaging = $DB_{electricity}$/kWh × 0.2 kWh/packaging
     EL of heater = DBelectricity/kWh × 1.5 kWh/heater
   - Total EL from the manufacture stage
     Sum of the EL from the water kettle assembly, and manufacturing of housing, packaging and heater.
     Here, as we took the 75% decision rules for mass inclusion, we must adjust the data for the three components.
     Adjusted EL = Water kettle assembly EL + (sum of EL for the manufacturing of housing, packaging and heater manufacturing)/0.75

III. Data from distribution stage
   Distance traveled = 3000 km
   Mode of transport = 40 ton truck
   EL of the distribution = DB 40 ton truck/(ton-km) × distance traveled (3,000 km) × water kettle weight (0.87 kg/(1,000 kg/ton))

IV. Data from product use stage
   Electricity used per use = 0.0545 kWh
   Total number of uses = 2250 uses
   EL of the product use = $DB_{electricity}$/kWh × 0.0545 kWh/use × 2,250 uses

V. Data from end of life stage
   Percent of waste incinerated = 20%
   Percent of waste landfilled = 30%
   Percent of waste recycled = 50%
   EL of incineration = $DB_{incineration}$/kg × 0.2 × 0.87 kg/water kettle
   EL of landfilling = $DB_{landfill}$/kg × 0.3 × 0.87 kg/water kettle
   EL of recycling = $DB_{recycling}$/kg × 0.5 × 0.87 kg/water kettle

VI. LCI results of the water kettle
   Sum of the EL from the use of raw materials, manufacture, distribution, product use and end of life stage is the life cycle inventory results of the water kettle. See Table 21.

2. Life cycle inventory analysis (8)

- Results of life cycle inventory analysis

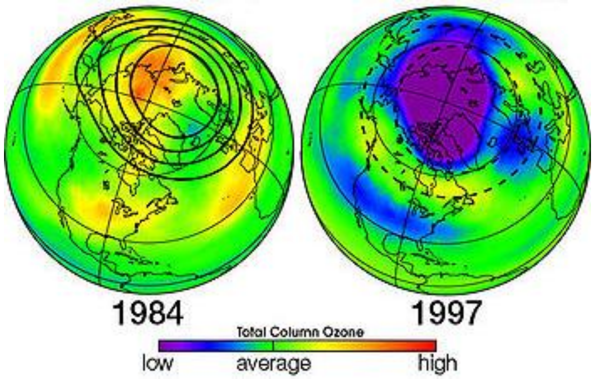
Table 21 Life cycle inventory analysis result of the water kettle (unit: g/water kettle).

Parameter	Use of raw materials	Manufacture	Distribution	Product use	End of life	Total
Crude oil	605.48		73.34		−63.71	615.11
Coal	124.64	169.94		6 069.94	7.00	6 371.52
Chromium	32.48					32.48
Iron	104.80				−92.22	12.58
CO_2	1 500.53	995.59	241.43	35 561.25	−154.93	38 143.87
Methane		1.83		65.24	1.71	68.78
CO				1.33		1.33
VOC	4.22					4.22
NO_x (Air)	5.46				0.11	5.57
SO_x (Air)	4.84		4.05	144.70	0.03	153.62

3. Life cycle impact assessment

- **Global warming (GW)**
  - Greenhouse gases such as CO_2
  - Kyoto protocol is being ratified

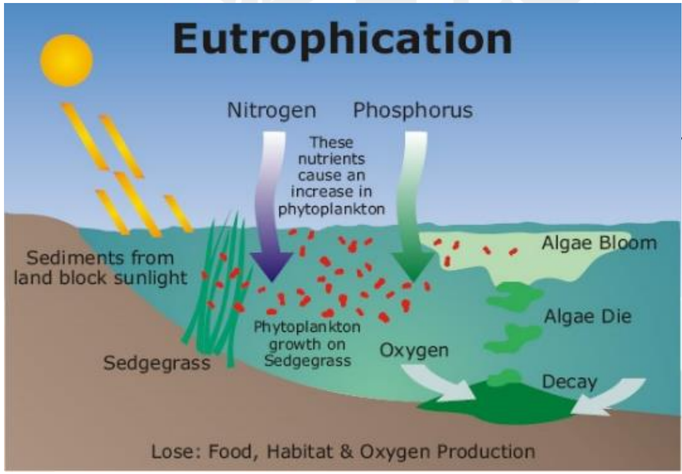
- **Ozone layer depletion (OD)**
  - CFC 11 (Freon, a refrigerant)
  - Skin cancer and mutation of plants



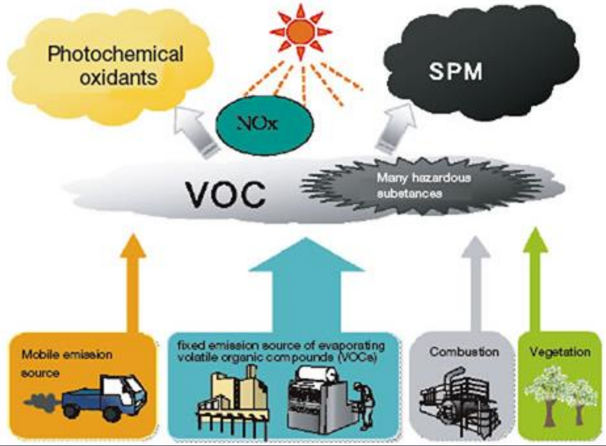
- **Acidification (AD)**
  - Increase in proton or hydrogen ion concentration in water by NO_x and SO_x

3. Life cycle impact assessment

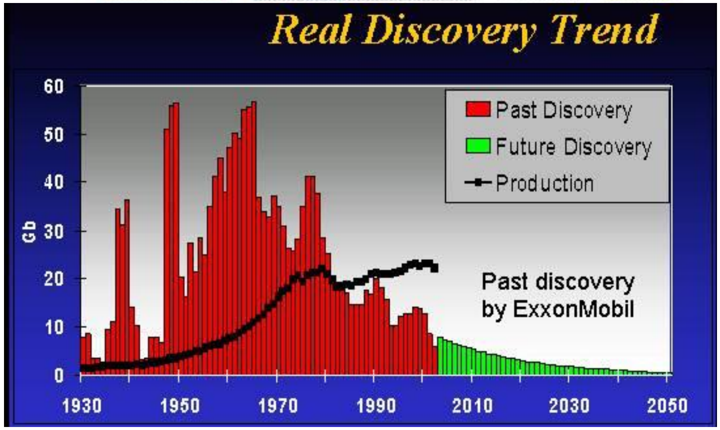
- **Eutrophication (EU)**
  - Increase in nutrient (nitrogen and phosphorous)
  - Excessive growth of Algae



- **Photochemical oxidant creation (POC)**
  - Smog
  - Hydrogen carbon from automobile



- **Abiotic resource depletion (ARD)**
  - Consumption of non-renewable resources such as crude oil



3. Life cycle impact assessment

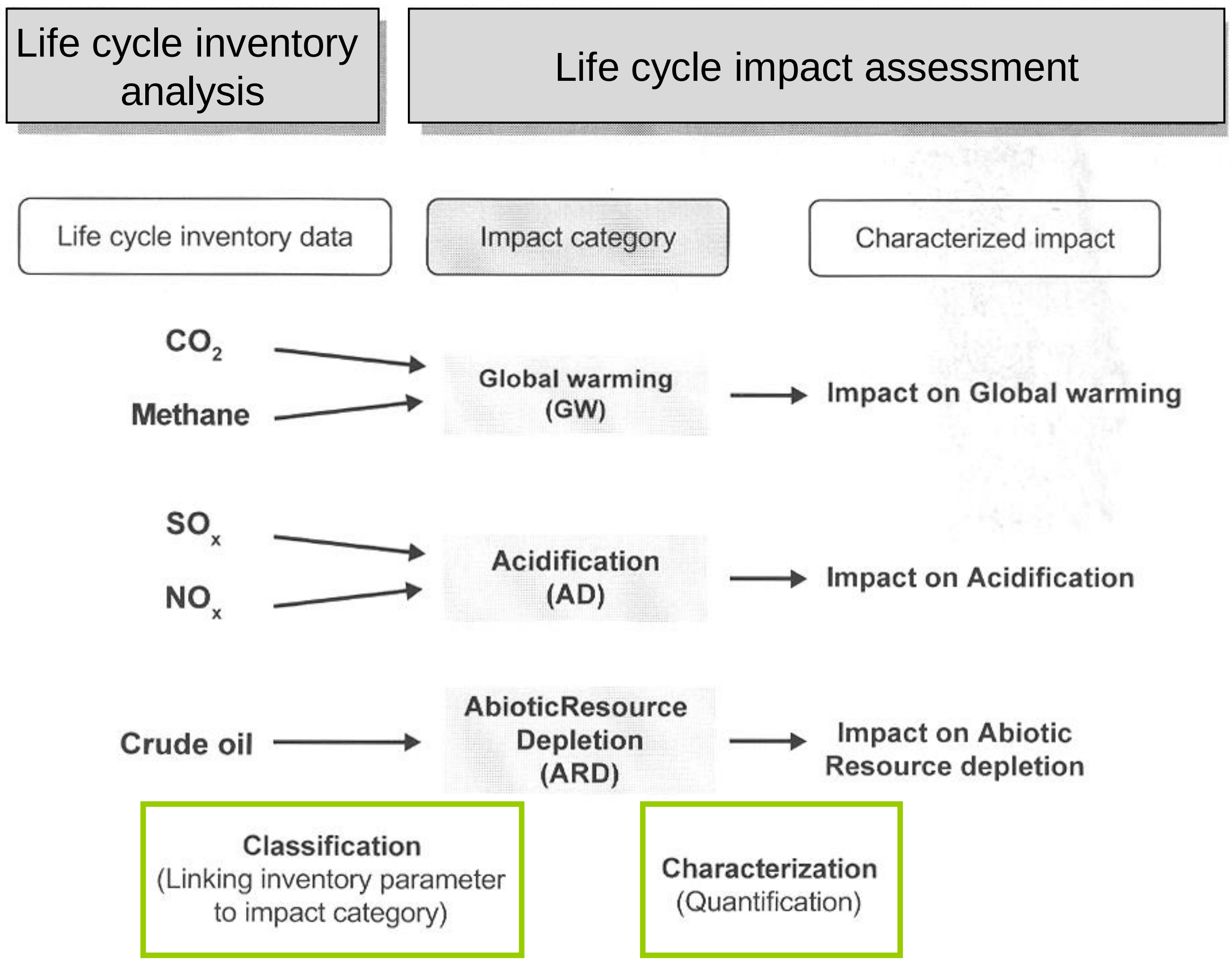


Figure 14 Relationship between life cycle inventory analysis and life cycle impact assessment.

3. Life cycle impact assessment (2)

- Classification

Table 22 Classification of the water kettle.

Parameter	*Impact categories*				
	GW	*AD*	*EU*	*POC*	*ARD*
Crude oil					✓
Coal					✓
Chromium					✓
Iron					✓
CO_2	✓				
Methane	✓			✓	
CO				✓	
VOC				✓	
NO_x		✓	✓	✓	
SO_x		✓			

EU: eutrophication
POC: photochemical oxidant

3. Life cycle impact assessment (3)

- Cause-effect chain
  - Example of acidification

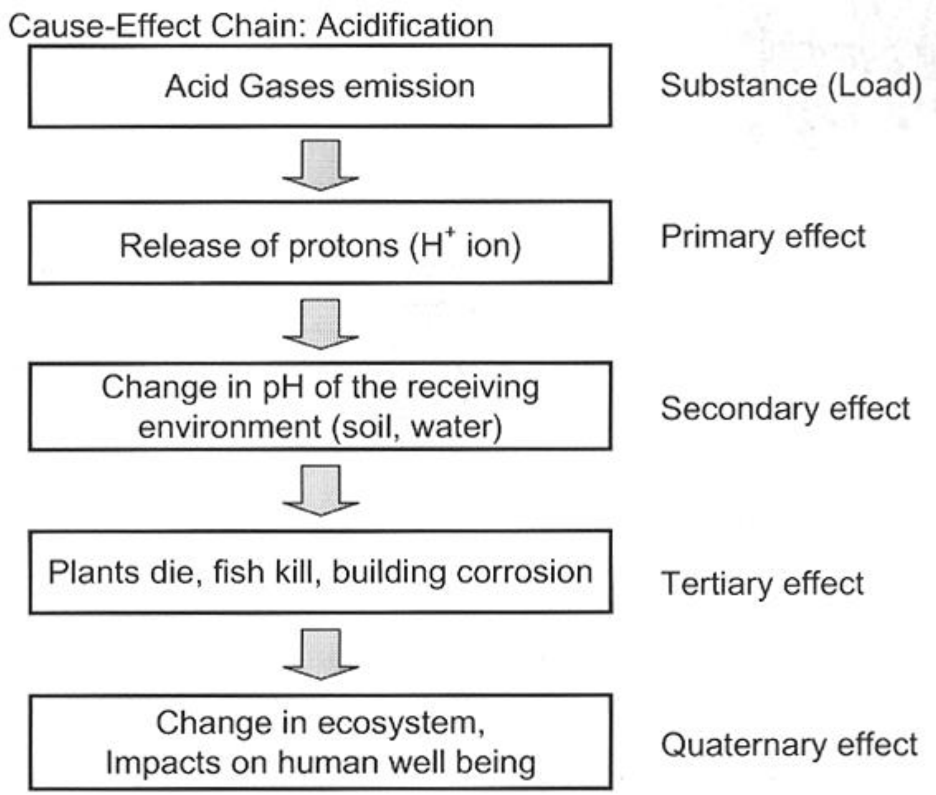


Figure 15 Cause-effect chain of acidifying gases in the environment.

3. Life cycle impact assessment (4)

- Typical impact categories

Table 23 Name and unit of characterization factor of typical impact categories.

Impact category	*Characterization factor name*	*Characterization factor unit*
Global warming	Global warming potential (GWP)	g CO_2-eq/g
Ozone layer depletion	Ozone depletion potential (ODP)	g CFC11-eq/g
Acidification	Acidification potential (AP)	g SO_2-eq/g
Eutrophication	Eutrophication potential (EP)	g PO_4^{3-}-eq/g
Photochemical oxidant	Photochemical oxidant creation potential (POCP)	g C_2H_4-eq/g
Abiotic resource depletion	Abiotic resource depletion potential (ADP)	1/yr*

(Note: * is the unit from U_j/D_j, where U_j = worldwide use of the jth resource, kg/yr; D_j = the size of the deposit of the jth resource, economically extractable, kg)

3. Life cycle impact assessment (5)

- Characterization factors

Table 24 Characterization factors used in the water kettle case.

Parameter	*Characterization factor*				
	GWP (g CO_2 eq/g)	*AP (g SO_2 eq/g)*	*EP (g PO_4^{3-} eq/g)*	*POCP (g ethene eq/g)*	*ADP (1/yr)*
Crude oil					0.0248
Coal					0.00344
Chromium					0.00381
Iron					0.00721
CO_2	1.00				
Methane	23.00			0.006	
CO				0.027	
VOC				0.416	
NO_x		0.70	0.13	0.028	
SO_x		1.00			

3. Life cycle impact assessment (6)

- CI = (load of inventory parameter) x (characterized factor of parameter)

Table 25 Characterized impact of the water kettle.

Parameter	*Load (from Table 21)*	*Characterized Impact (CI)*									
		GW (g CO_2 eq/water kettle)		*AD (g SO_2 eq/water kettle)*		*EU (g PO_4^{3-} eq/ water kettle)*		*POC (g ethene eq/ water kettle)*		*ARD (g/water kettle-yr)*	
		GWP	*CI*	*AP*	*CI*	*EP*	*CI*	*POCP*	*CI*	*ADP*	*CI*
Crude oil	615.11									0.0248	15.25
Coal	6 371.52									0.00344	21.92
Chromium	32.48									0.00381	0.12
Iron	12.58									0.00721	0.09
CO_2	38 143.87	1.00	38 143.87								
Methane	68.78	23.00	1 581.94					0.006	0.41		
CO	1.33							0.027	0.04		
VOC	4.22							0.416	1.76		
NO_x	5.57			0.70	3.90	0.13	0.72	0.028	0.16		
SO_x	153.62			1.00	153.62						
Total			39 725.81		157.52		0.72		2.37		37.38

3. Life cycle impact assessment (7)

Table 26 Characterized impact of the water kettle per life cycle stage.

Impact category		*Life cycle stage*					*Total*
		Use of raw materials	*Manufacture*	*Distribution*	*Product use*	*End of life*	
GW	g CO_2 eq/ water kettle	1500.53	1037.65	241.43	37 061.70	−115.50	39 725.81
AD	g SO_2 eq/ water kettle	8.66	4.05		144.70	0.11	157.52
EU	g PO_x^{3-} eq/ water kettle	0.71				0.01	0.72
POC	g ethene eq/ water kettle	1.92	0.00	0.04	0.40	0.01	2.37
ARD	g/water kettle-yr	16.32	0.58	1.82	20.88	−2.22	37.38

4. Life cycle interpretation

Table 27 Characterized impact of the global warming impact category of the water kettle (unit: g CO_2-eq/water kettle).

Inventory parameter	Unit processes and activities					Sum
	Use of raw materials	Manufacture	Distribution	Product use	End of life	
CO_2	1 500.53	995.59	241.43	35 561.25	−154.93	38 143.87
CH_4		42.06		1 500.45	39.43	1 581.94
Sum	1 500.53	1 037.65	241.43	37 061.70	−115.50	39 725.81

Table 28 Percent contribution by each entry on the matrix to the total global warming impact category of the water kettle (unit: %).

Inventory parameter	Unit processes and activities					Sum
	Use of raw materials	Manufacture	Distribution	Product use	End of life	
CO_2	3.77	2.51	0.61	89.52	−0.39	96.02
CH_4		0.10		3.78	0.10	3.98
Sum	3.77	2.61	0.61	93.30	−0.29	100

Above 1% impact is considered as a significant issue

4. Life cycle interpretation (2)

- Normalization
  - N: an impact of an impact category from all the different products in a given geographical region
    - Normalization reference of an impact category, g x –eq/(person equivalent-year)
  - N = Σ[(load of a parameter per year) x (characterization factor of the parameter)] / (population size of the geographical region)

- Normalized impact
  - NI = CI / N
  - Represents degree of relative impact caused by the product to the total impact of the geographical region

- Normalization enables direct comparison of the magnitude of the impact among different categories

4. Life cycle interpretation (3)

- Normalization reference (per person equivalent year) (1995 data)
  - GW: 5660 kg CO_2-eq
  - AD: 56.4 kg SO_2-eq
  - EU: 8.9 kg PO_4^{3-}-eq
  - POC: 7.4 kg ethene-eq
  - ARD: 18.7 kg/year
  - (MOCIE 2002)

→ Table 26

GW: 1500.53 g CO_2-eq/5660kg = 265.12 e-6

Table 29 Normalized impact of water kettle per life cycle stage.

Impact category	Total (millionth pe-yr/water kettle)					Total
	Use of raw materials	Manufacture	Distribution	Product use	End of life	
GW	265.12	183.33	42.66	6548.00	−20.41	7018.70
AD	153.52	71.83		2565.60	1.95	2792.90
EU	79.78				1.12	80.90
POC	259.46	0.00	5.41	54.05	1.35	320.27
ARD	872.49	31.26	97.33	1116.58	−118.72	1998.94

4. Life cycle interpretation (4)

- Weighting
  - Assignment of relative significance to the impact categories based on social, ethical, and political values
- Weighted impact
  - WI = weight of the impact category x NI of the impact category
- Weights can be determined by panel members

Table 30 Weighted impact of the water kettle per impact category.

Impact category	*Normalized impact (millionth pe-yr/ water kettle)*	*Weight*	*Weighted impact (millionth pe-yr/ water kettle)*	*Fraction (%)*
GW	7018.70	0.29	2035.42	65.76
AD	2792.90	0.16	446.86	14.44
EU	80.90	0.14	11.33	0.37
POC	320.27	0.13	41.64	1.35
ARD	1998.94	0.28	559.70	18.08
Total			3094.95	100.00

4. Life cycle interpretation (5)

- Weighted impact for each life cycle
- Normalized impact in Table 29 x weight

Table 31 Weighted impact of the water kettle per life cycle stage (unit: millionth pe-yr/water kettle).

Impact category	*Use of raw materials*	*Manufacture*	*Distribution*	*Product use*	*End of life*	*Total*
GW	76.03	54.02	12.37	1898.92	−5.92	2035.42
AD	24.73	11.32		410.50	0.31	446.86
EU	11.17				0.16	11.33
POC	33.73	0.00	0.70	7.03	0.18	41.64
ARD	242.37	10.68	27.25	312.64	−33.24	559.70
Total	388.03	76.02	40.32	2629.09	−38.51	3094.95

4. Life cycle interpretation (6)

- Completeness check
  - Identify each stage in the process tree

Table 32 Completeness check result of the water kettle.

Unit process	*Complete?*	*Action required?*
PP production	A	
Housing	B	Check inventory
Stainless steel production	A	
Heater manufacturing	B	Check inventory
Cardboard production	A	
Packaging	B	Check inventory
Electricity	A	
Manufacture	A	
Distribution	C	Check inventory
Product use	B	Check inventory
Incineration	C	Check inventory
Landfill	C	Check inventory
Recycling	C	Check inventory

(Note: A represents 100% and E 0% completeness, all qualitative)

4. Life cycle interpretation (7)

- Sensitivity and consistency check

Table 33 Sensitivity check result of the water kettle for the allocation method.

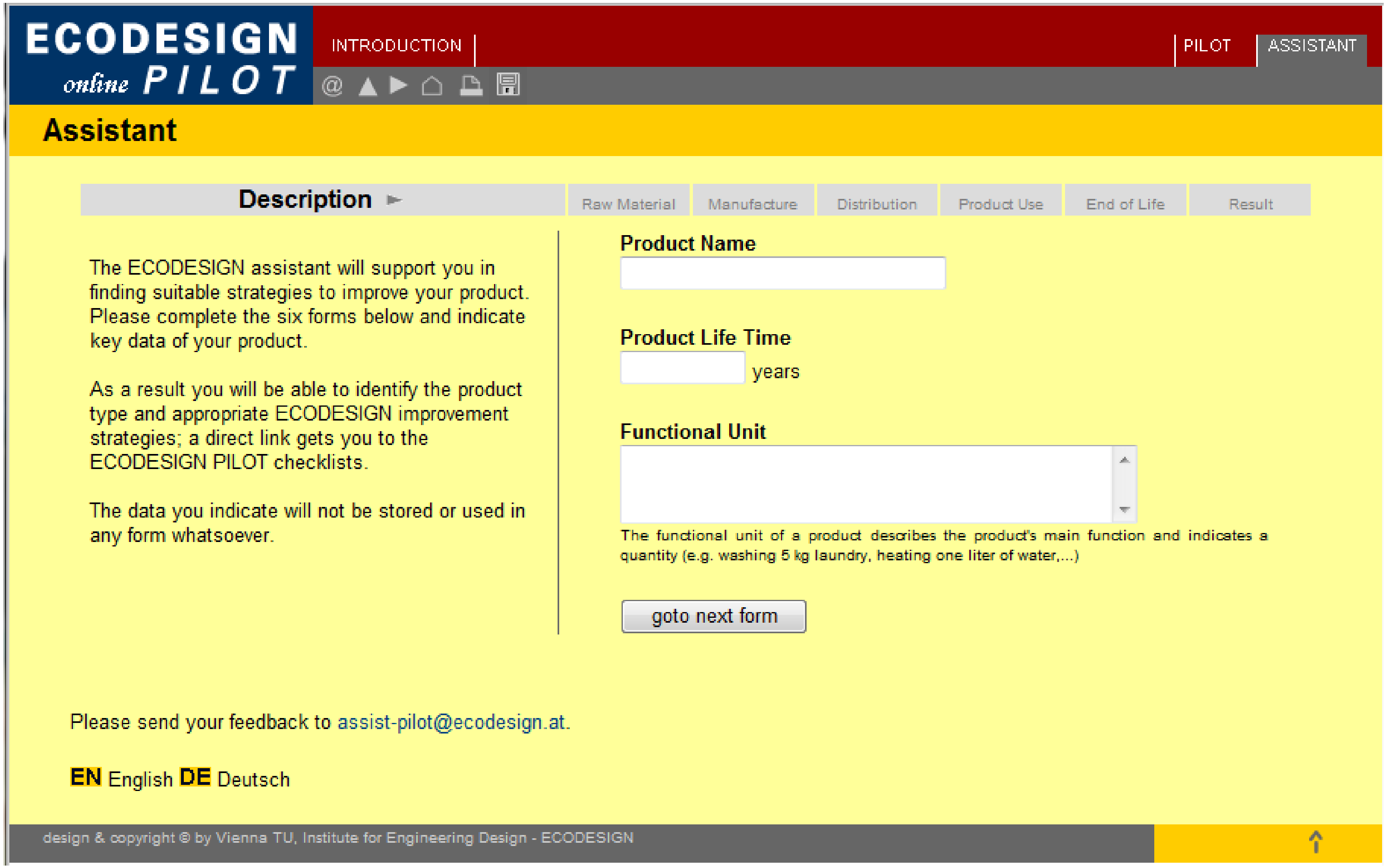
Allocation criteria	*Weighted impact (unit: millionth pe-yr/water kettle)*
Economic criteria	3094.95
Mass criteria	3123.41
Sensitivity (%)	0.92

Table 34 Consistency check result of the water kettle.

Item	*Check*		*Action required?*
Data source	Database	OK	No action
Data accuracy	Good	OK	No action
Database age	5 years	OK	No action
Characterization factor	OK		No action
Characterization method	OK		No action

Eco-design pilot's assistant

- http://www.ecodesign.at/assist/assistent



Raw materials

Table 41 Material classes (ECODESIGN PILOT's Assistant).

	Metals	*Plastics*	*Other materials*
Class I			• Concrete • Wood, solid • Plaster
Class II	• Electric steel (secondary) • Aluminum (secondary) • Steel plate (90% recycled)		• Porcelain • Glass, bottles (recycled) • Sheet glass, (float glass) • Glass fiber • Linoleum • Cardboard • Paper (100% recycled) • Glass, container – (new)
Class III	• Steel (80% primary) • Steel (primary) • Steel, low-alloy		• Paper (65% recycled) • Leather • Rubber, green • Caoutchouc • Paper, free from chlorine • Rubber, raw • Coolant R134a • Ammonia NH3 • Fuel oil • Gasoline, unleaded

Raw materials (2)

Table 41 (Continued)

	Metals	Plastics	Other materials
Class IV	• Cast iron • Sheet steel, galvanized • Cast steel	• PVC • HDPE • PP • LDPE • PPE/PS • PS • PET • SAN	• Rubber • Latex • Porcelain • Cellulose • Paper
Class V	• Copper (secondary) • Lead (50% primary) • Ferrochromium (53% Cr)	• PB • ABS • PE, foam • PUR, HR foam • PVDC • PU, non-rigid • PUR • PMMA (acrylic) • PC • PA 6.6 (nylon) • EP (epoxy resin) • PA (nylon)	• Glass fiber reinforced plastics (GRP) • Technical ceramic material
Class VI	• Steel, V2A: 18% Cr, 9% Ni • Steel, V4A: 17% Cr, 12% Ni		• Carbon fiber

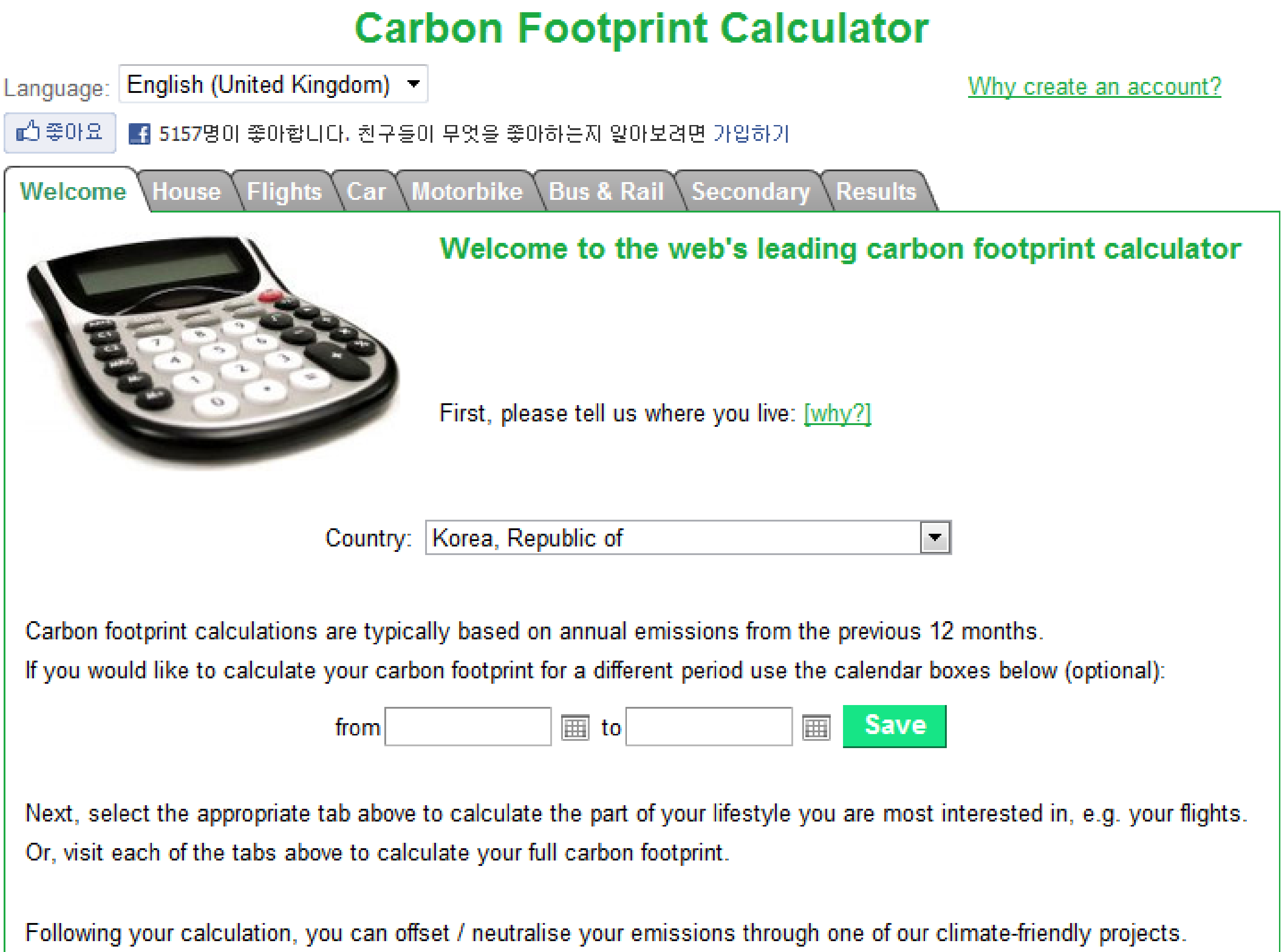
Raw materials (3)

Table 41 (Continued)

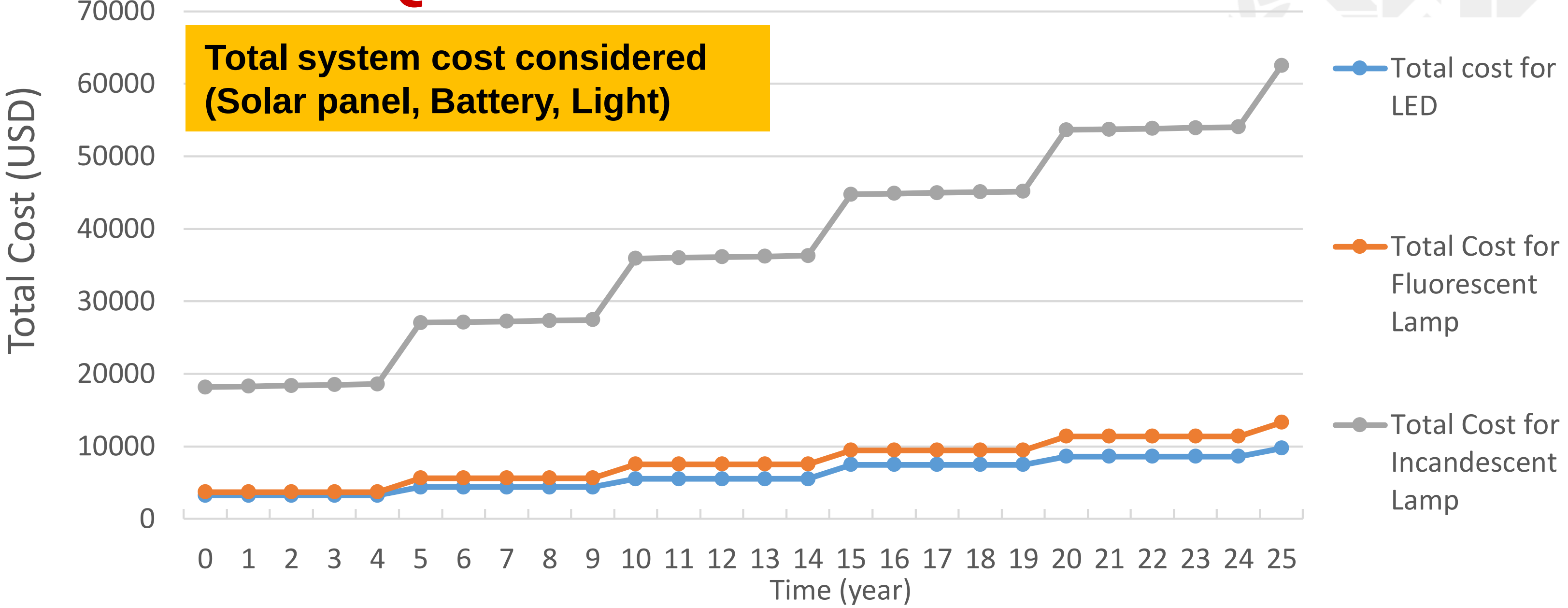
	Metals	Plastics	Other materials
	• Ferronickel (33% Ni) • Zinc alloys • Aluminum and Al-alloys • Steel, high-alloy (stainless) • Chromium • Molybdenum • Magnesium alloys • Copper (primary) and cables • Metal powder		
Class VII	• Titanium alloys • Copper alloys • Zinc • Copper alloys, bronze • Nickel and Ni-alloys • Silver		
Class VIII	• Palladium • Platin • Gold • Rhodium		

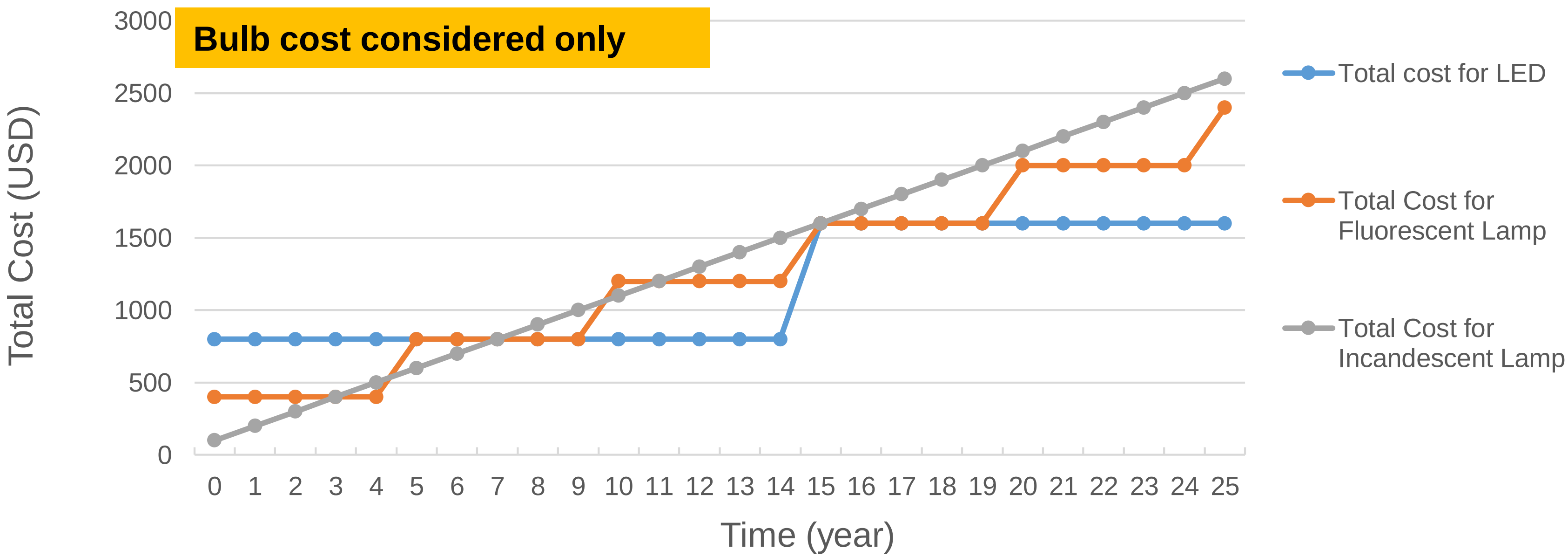
Carbon Footprint Calculator

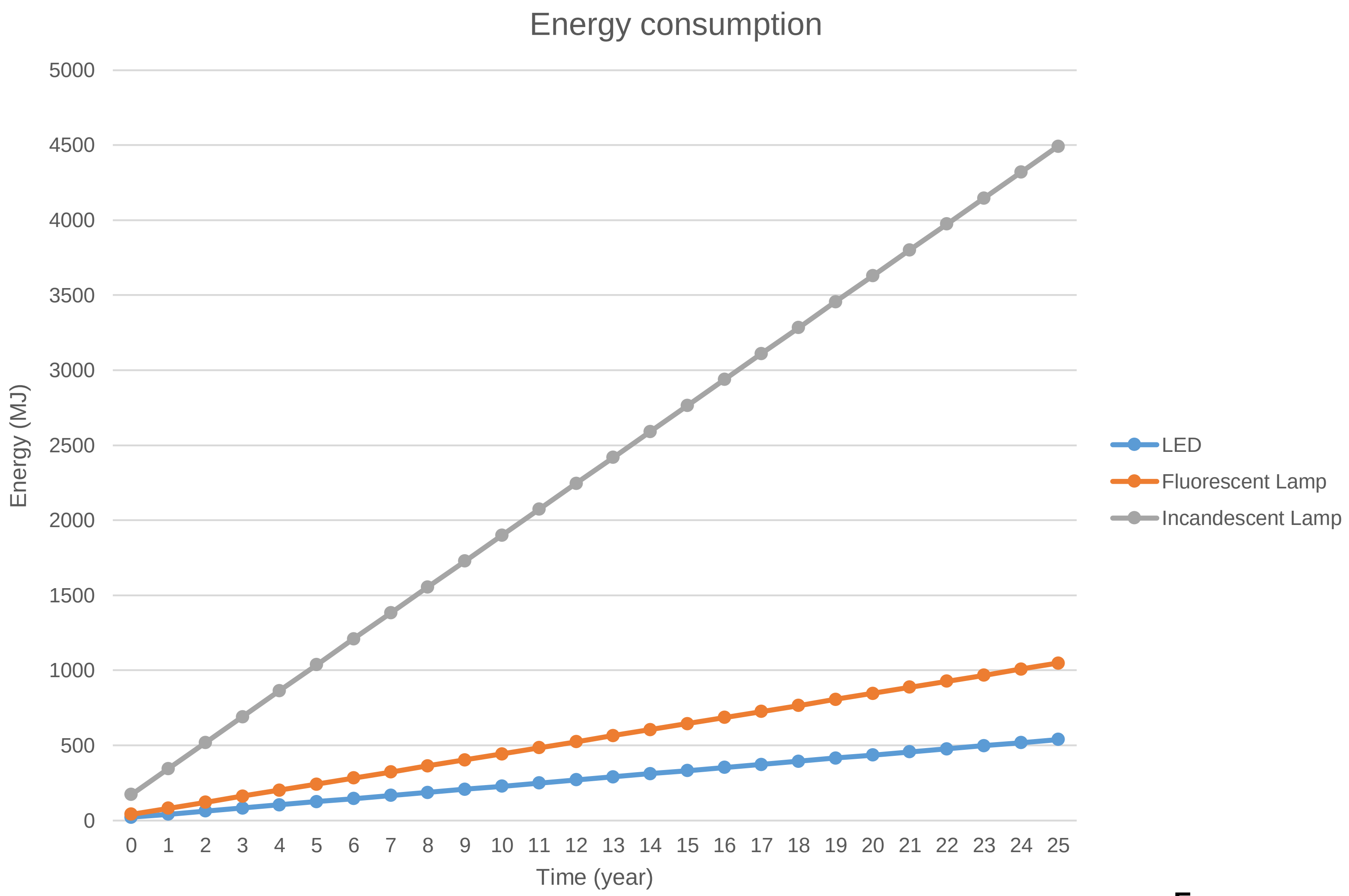
- http://www.carbonfootprint.com/



Solution for Quiz







Energy consumption
Bulb considered only