The CES EduPack Eco Audit Tool —A White Paper

Mike Ashby[1,2], Patrick Coulter[2], Nick Ball[2], and Charlie Bream[2]

1. *Engineering Department, University of Cambridge, Trumpington Street, Cambridge CB2 1PZ, UK*
2. *Granta Design, 300 Rustat House, 62 Clifton Rd, Cambridge, CB1 7EG UK*

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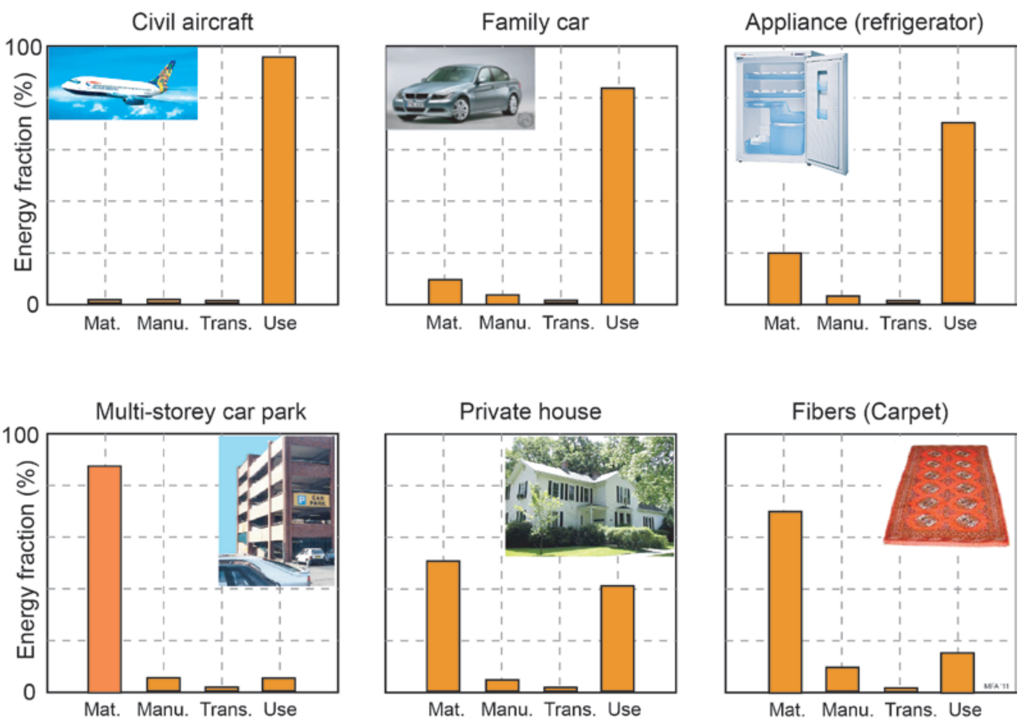

Abstract

The CES EduPack Eco Audit Tool enables the first part of a two-part strategy for selecting materials for eco-aware product design. The second part of the strategy is implemented through the CES EduPack selection software, described elsewhere (1, 2, 3). This white paper gives the background, describes the two-part strategy and explains the operation of the Eco Audit Tool, which draws on the same database of material and process properties as CES EduPack, ensuring consistency. The use of the tool is illustrated with case studies. The approach described provides an excellent basis for teaching students key eco design concepts. More can be found in Reference (1).

Contents

1. Introduction

All human activity has some impact on the environment in which we live. The environment has some capacity to cope with this, so that a certain level of impact can be absorbed without lasting damage. But it is clear that current human activities exceed this threshold with increasing frequency, diminishing quality of life and threatening the well being of future generations. Part, at least, of this impact derives from the manufacture, use, and disposal of *products*, and products, without exception, are made from *materials*.

Materials consumption in the United States now exceeds 10 tonnes per person per year. The average level of global consumption is about 8 times smaller than this but is growing twice as fast. The materials and the energy needed to make and shape them are drawn from *natural resources*: ore bodies, mineral deposits, fossil hydrocarbons. The earth's resources are not infinite, but until recently, they have seemed so: the demands made on them by manufacture throughout the 18th, 19th, and early 20th century appeared infinitesimal, the rate of new discoveries always outpacing the rate of consumption. This perception has now changed: warning flags are flying, danger signals flashing.

To develop tools to analyze the problem and respond to it, we must first examine the materials life cycle and consider how to apply life cycle analysis. The materials life cycle is sketched in Figure 1. Ore and feedstock are mined and processed to yield materials. These are manufactured into products that are used and at the end of life, discarded, recycled or (less commonly) refurbished and reused. Energy and materials are consumed in each phase of life, generating waste heat and solid, liquid, and gaseous emissions.

2. Life cycle analysis and its difficulties

The environmental impact caused by a product is assessed by environmental life cycle assessment (LCA).

Life cycle assessment techniques, now documented in standards (ISO 14040, 1997, 1998), analyze the eco impact of products once they are in service. They have acquired a degree of rigor, and now deliver essential data documenting the way materials influence the flows of energy and emissions of Figure 1. It is standard practice to process these data to assess their contributions to a number of known environmental impacts: ozone depletion, global warming, acidification of soil and water, human toxicity, and more (nine categories in all), giving output that looks like

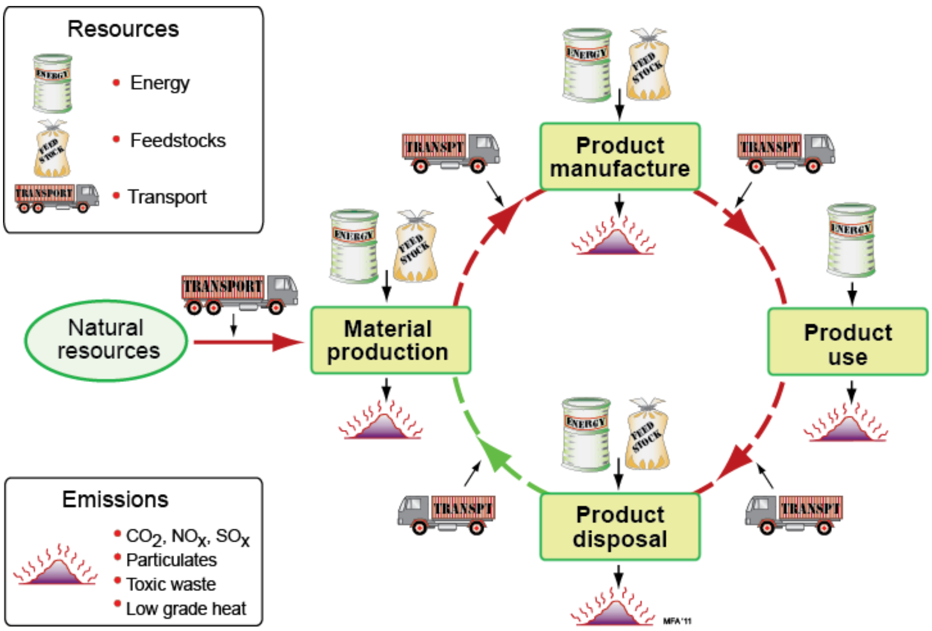

Figure 1. The material life-cycle: material creation, product manufacture, product use, and a number of options for product disposal at end of life. Transport is involved between the stages.

Figure 2.

Despite the formalism that attaches to LCA methods, the results are subject to considerable uncertainty. Resource and energy inputs can be monitored in a straightforward and reasonably precise way. The emissions rely more heavily on sophisticated monitoring equipment—few are known to better than 10%. Assessments of impacts depend on values for the marginal effect of each emission on each impact category; many of these have much greater uncertainties. Moreover, a full LCA is time-consuming, expensive, and requires much detail, and it cannot cope with the problem that 80% of the environmental burden of a product is determined in the early stages of design when many decisions are still fluid. LCA is a product assessment tool, not a design tool.

And there is a further difficulty: what is a designer supposed to do with these numbers? The designer, seeking to cope with the many interdependent decisions that any design involves, inevitably finds it hard to know how best to use data of this type. How are CO_2 and SO_x productions to be balanced against resource depletion, energy consumption, global warming potential, or human toxicity?

This perception has led to efforts to condense the eco information about a material's production into a single measure or *indicator*, normalizing and weighting each source of stress to give the designer a simple, numeric ranking. The use of a single-valued indicator is criticized by some on the grounds that there is no agreement on normalization or weighting factors and that the method is opaque since the indicator value has no simple physical significance.

On one point, however, there is a degree of international agreement: a commitment to a progressive reduction in carbon emissions, generally interpreted as meaning CO_2. At the national level the focus is more on reducing energy consumption, but since this and CO_2 production are closely related, reducing one generally reduces the other. Thus there is a certain logic in basing design decisions on energy consumption or CO_2 generation; they carry more conviction than the use of a more obscure indicator, as evidenced by the now-standard reporting of both energy efficiency and the CO_2 emissions of cars, and the energy rating and ranking of appliances. We shall follow this route.

The need, then, is for a product-assessment strategy that addresses current concerns and combines acceptable cost burden with sufficient precision to guide decision-making. It should be flexible enough to accommodate future refinement and simple enough to allow rapid "What-if" exploration of alternatives. To achieve this it is necessary to strip-off much of the detail, multiple targeting, and complexity that makes standard LCA methods so cumbersome.

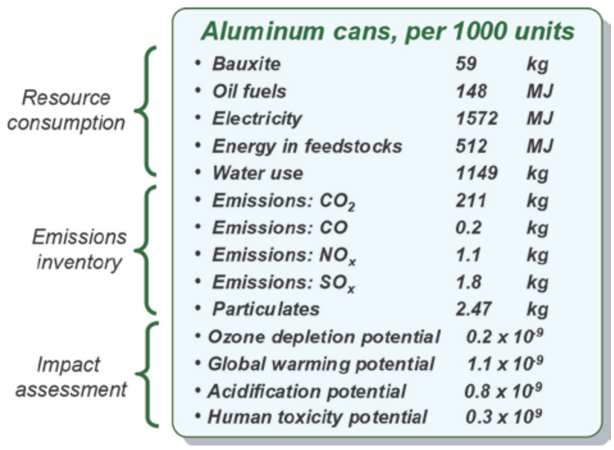

Figure 2. Typical LCA output showing three categories: resource consumption, emission inventory, and impact assessment (data in part from reference (4)).

3. The approach

The approach developed here has three components.

1. Adopt simple measures of environmental stress.

Section 2 points to the use of energy or CO_2 footprint as logical choices for measuring environmental stress, rather than combined indicators. If we wanted to pick just one of these, energy has the merit that it is the easiest to monitor, can be measured with relative precision and, with appropriate precautions, can when needed be used as a proxy for CO_2.

2. Distinguish the phases of life.

Figure 3 suggests the breakdown, assigning a fraction of the total life-energy demands of a product to material creation, product manufacture, transport, and product use and disposal. Product disposal can take many different forms, some carrying an energy penalty, some allowing energy recycling or recovery. When this distinction is made, it is frequently found that one of phases of

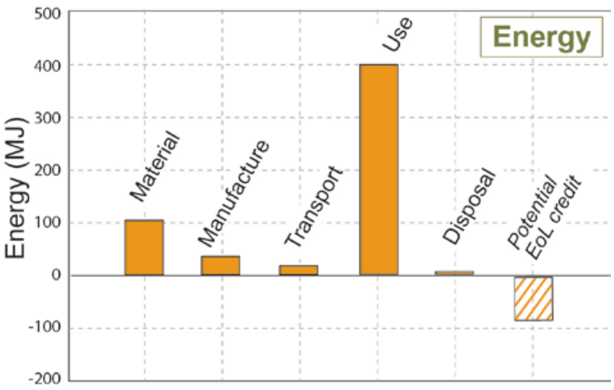

Figure 3. Breakdown of energy into that associated with each life-phase.

Figure 1 dominates the picture. Figure 4 presents the evidence. The upper row shows an approximate energy breakdown for three classes of energy-using products: a civil aircraft, a family car, and an appliance: for all three the use-phase consumes more energy than the sum of all the others. The lower row shows products that require energy during the use-phase of life, but not as intensively as those of the upper row. For these, the embodied energies of the materials of which they are made often dominate the picture. Two conclusions can be drawn. The first: one phase frequently dominates, accounting for

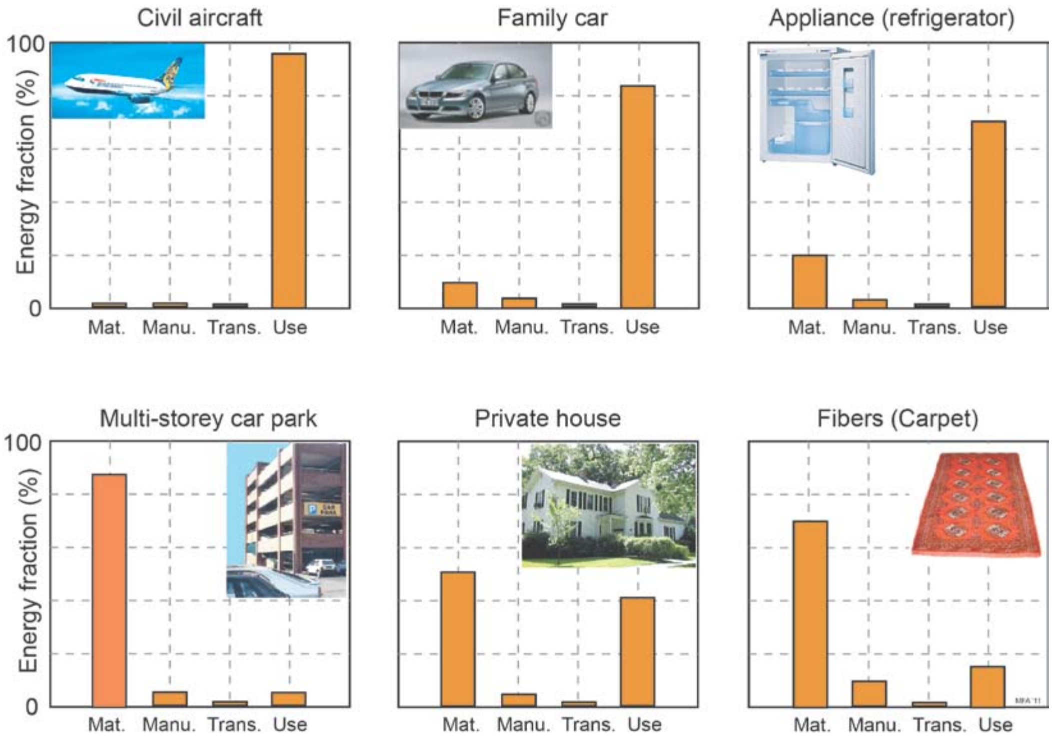

Figure 4. Approximate values for the energy consumed at each phase of Figure 1 for a range of products (data from refs. (5) and (6)). The disposal phase is not shown because there are many alternatives for each product.

60% or more of the energy—often much more. If large energy savings are to be achieved, it is the dominant phase that becomes the first target since it is here that a given fractional reduction makes the biggest contribution. The second: when differences are as great as those of Figure 4, great precision is not necessary—modest changes to the input data leave the ranking unchanged. It is the nature of people who *measure* things to wish to do so with precision, and precise data must be the ultimate goal. But it is possible to move forward without it: precise judgments can be drawn from imprecise data.

3. Base the subsequent action on the energy or carbon breakdown.

Figure 5 suggests how the strategy can be implemented. If material production is the dominant phase, then minimizing the mass of material used and choosing materials with low embodied energy are logical ways forward. If manufacture is an important energy-using phase of life, reducing processing energies becomes the prime target. If transport makes a large contribution, then seeking a more efficient transport mode or reducing distance becomes the first priority. When the use-phase dominates the strategy is that of minimizing mass (if the product is part of a system that moves), or increasing thermal efficiency (if a thermal or thermo-mechanical system), or reducing electrical losses (if an electro-mechanical system). In general the best material choice to minimize one phase will not be the one that minimizes the others, requiring trade-off methods to guide the choice. A full description of these and other methods for materials selection can be found in reference (2).

Implementation requires tools. Two sets are needed, one to perform the eco audit sketched in the upper part of Figure 5, the other to enable the analysis and selection sketched in the lower part. The purpose of this white paper is to describe the first: the Eco Audit Tool.

4. The Eco Audit Tool

Figure 6 shows the structure of the tool. The inputs are of two types. The first are drawn from a user-entered *bill of materials*, *process choice*, *transport requirements* and *duty cycle*

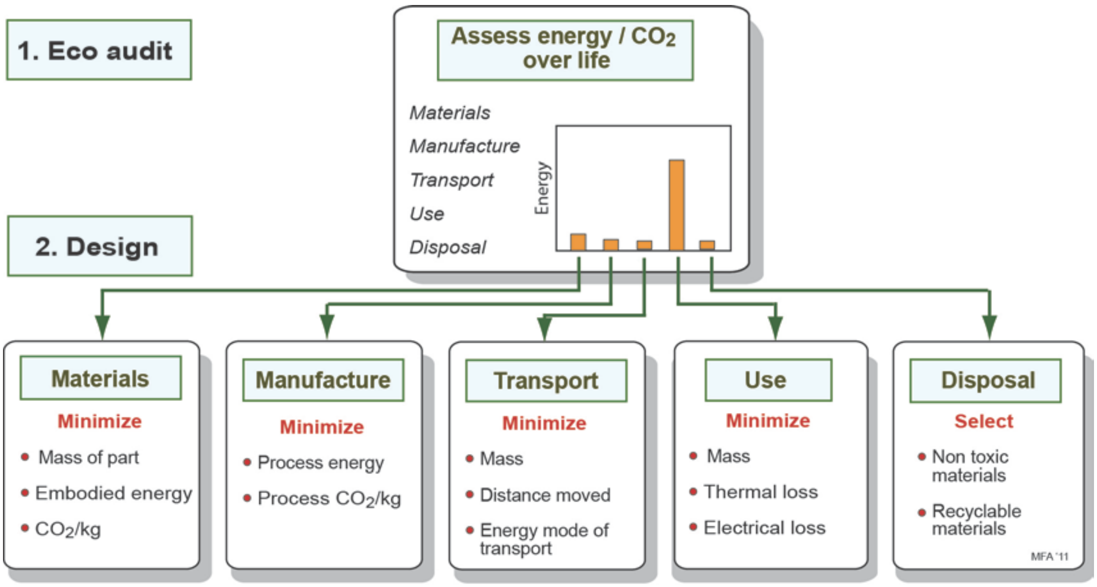

Figure 5. Rational approaches to the eco design of products start with an analysis of the phase of life to be targeted. Its results guide redesign and materials selection to minimize environmental impact.

(the details of the energy and intensity of use), and disposal route. Data for embodied energies and process energies are drawn from a database of material properties; those for the energy and carbon intensity of transport and the energy sources associated with use are drawn from look-up tables. The outputs are the energy or carbon footprint of each phase of life, presented as bar charts and in tabular form.

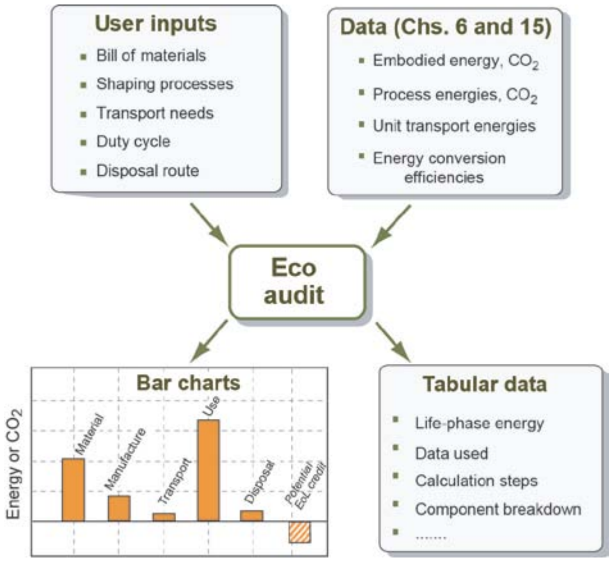

Figure 6. The Eco Audit Tool. The model combines user-defined inputs with data drawn from databases of embodied energy of materials, processing energies, and transport type to create the energy breakdown. The same tool can be used for an assessment of CO_2 footprint.

The tool in detail. The tool is opened from the "Tools" menu of the CES EduPack software toolbar by clicking on "Eco Audit". Figure 7 (overleaf) is a schematic of the user interface that shows the user actions and the consequences. There are four steps, labeled 1, 2, 3, and 4. Actions and inputs are shown in red.

Step 1, material and manufacture allows entry of the mass, the material and primary shaping process for each component. The component name is entered in the first box. The material is chosen from the pull-down menu of box 2, opening the database of materials properties[1]. Selecting a material from the tree-like hierarchy of materials causes the tool to retrieve and store its embodied energy and CO_2 footprint per kg. The primary shaping process is chosen from the pull-down menu of box 3, which lists the processes relevant for the chosen material; the tool again retrieves energy and carbon footprint per kg. The last box allows the component weight to be entered in kg. On completing a row-entry a new row appears for the next component.

On a first appraisal of the product it is frequently sufficient to enter data for the components with the greatest mass, accounting for perhaps 95% of the total. The residue is included by adding an entry for "residual components" giving it the mass required to bring the total to 100% and selecting a proxy material and process: "polycarbonate" and "molding" are good choices because their energies and CO_2 lie in the mid range of those for commodity materials.

The tool multiplies the energy and CO_2 per kg of each component by its mass, and totals them. In its present form the data for materials are comprehensive. Those for processes are rudimentary.

Dealing with end of life. There are five options for disposal at the end of life: *landfill, combustion for energy recovery, recycling, re-engineer,* and *reuse*. A product at end of *first life* (Figure 8) has the ability to return part or all of its embodied energy. This at first sounds wrong—much of the "embodied" energy was not *embodied* at all but was lost as low-grade heat via the inefficiencies of the processing plant, and even when it is still there, it is, for metals and ceramics, inaccessible since the only easy way to recover energy directly is by

[1] One of the CES EduPack Materials databases, depending on which was chosen when the software was opened.

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combustion, not an option for steel, concrete, or brick. But think of it another way. If the materials of the product are recycled or the product itself is re-engineered or reused, a need is filled without drawing on virgin material, thereby saving energy. Carbon release works in the same way, with one little twist: one end-of-life option, combustion, recovers some energy but in doing so it releases CO_2.

Recycling passes material from one life-cycle to the next. In general it takes less energy and releases less carbon to recycle a unit of material than it takes to create the same quantity of virgin material from ores and feedstock—it is this that makes recycling attractive. But is the saved energy and CO_2 to be credited to the first life-cycle or the second? It can't be credited to both, since that would be to count it twice. This difficulty is analyzed in depth in references (2) and (3). Here we describe the way the Eco Audit Tool deals with the problem.

Recycling at end of life is a future benefit, one that may not be realized for many years or, indeed, at all. If the concern is for *present* resources, energy demands and climate-changing emissions, then it does not make sense to use the substitution method. We therefore assign a credit to the use of materials with recycle content at the start of life, and give no credit for recycling at the end This focuses attention on the present, not the future, it avoids double counting and it conforms to the European guide-lines on assessing carbon footprint known as PAS 2050 and BSI 2008.

But this choice still leaves us with a difficulty. One purpose of an eco-audit is to guide *design* decisions. Designers that strive to design products using recycled materials will wish the eco-audit to reflect this, as the recycled content method does. On the other hand, designers that strive to make disassembly easy and to use materials that recycle well would also want the audit to reflect that, and the recycled content method fails to do so. To overcome this we show bars for the energy and carbon contributions to the first life as bars of solid colors, and show the potential energy and carbon saving (or penalty) arising from the end-of-life (EoL) choice as a separate, cross-hatched bar as in Figure 8.

Step 2, transport allows for transportation of the product from manufacturing site to point of sale. The tool allows multi-stage transport (e.g., shipping then delivery by truck). To use it, the stage is given a name, a transport type is selected from the pull-down "transport type" menu and a distance is entered in km or miles. The tool retrieves the energy / tonne.km and the CO_2 / tonne.km for the chosen transport type from a look-up table and multiplies them by the product weight and the distance travelled, finally summing the stages.

Step 3, the use phase requires a little explanation. There are two different classes of contribution.

Some products are (normally) static but require energy to function: electrically powered household or industrial products like hairdryers, electric kettles, refrigerators, power tools, and space heaters are examples. Even apparently non-powered products, like household furnishings or unheated buildings, still consume some energy in cleaning, lighting, and maintenance. The first class of contribution, then, relates to the power consumed by, or on behalf of, the product itself.

The second class is associated with transport. Products that form part of a transport system add to its mass and so augment its energy consumption and CO_2 burden.

The user-defined inputs of step 3 enable the analysis of both. Ticking the "static mode" box opens an input window. The primary sources of energy are taken to be fossil fuels (oil, gas). The energy consumption and CO_2 burden depend on a number of efficiency factors. When energy is converted from one form to another, some energy may be lost.

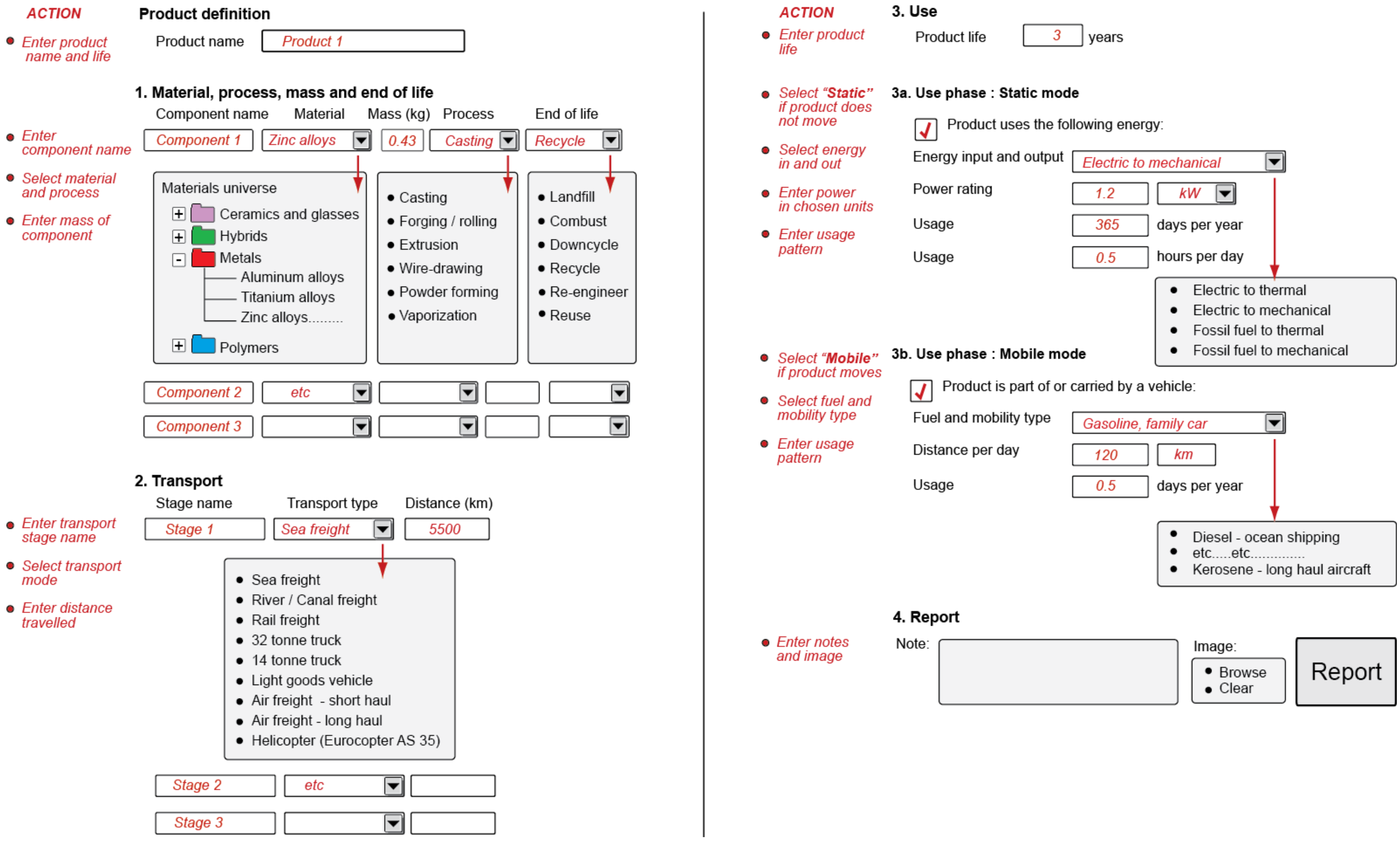

Figure 7. The Eco Audit Tool.

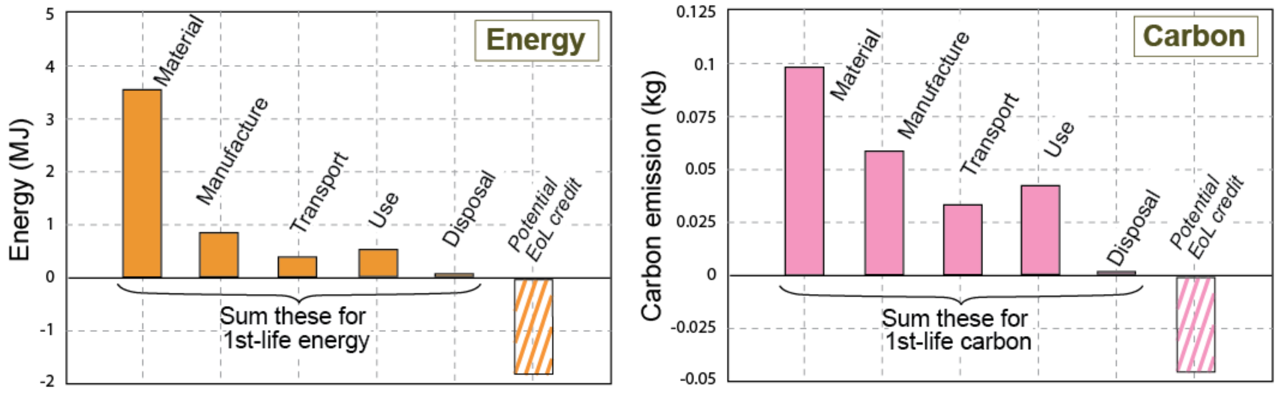

Figure 8. The 1st-life energy and carbon emissions, compared with potential end-of-life credit.

When fossil fuel or electricity are converted into heat, there are no losses—the efficiency is 100%. But when energy in the form of fossil fuel is converted to electrical energy the conversion efficiency is, on average[2], about 33%. The direct conversion of primary energy to mechanical power depends on the input: for electricity it is between 85 and 90%; for fossil fuel it is, at best, 40%. Selecting an energy conversion mode causes the tool to retrieve the efficiency and multiply it by the power and the duty cycle—the usage over the product life—calculated from the life in years times the days per year times the hours per day.

Products that are part of a transport system carry an additional energy and CO_2 penalty by contributing to its weight. The mobile mode part of step 3 gives a pull-down menu to select the fuel and mobility type. On entering the usage and daily distance the tool calculates the necessary energy.

Step 4, the final step, clicking "report" completes the calculation. The Appendix shows example output.

5. Case studies

An eco audit is a fast initial assessment. It identifies the phases of life—material, manufacture, transport, and use—that carry the highest demand for energy or create the greatest burden of emissions. It points the finger, so to speak, identifying where the greatest gains might be made. Often, one phase of life is, in eco terms, overwhelmingly dominant, accounting for 60% or more of the energy and carbon totals. This difference is so large that the imprecision in the data and the ambiguities in the modeling are not an issue; the dominance remains even when the most extreme values are used. It then makes sense to focus first on this dominant phase, since it is here that the potential innovative material choice to reduce energy and carbon are greatest. As we shall see later, material substitution has more complex aspects—there are trade-offs to be considered—but for now we focus on the simple audit.

This section outlines case studies that bring out the strengths and weaknesses of the Eco Audit Tool. Its use is best illustrated by a case study of extreme simplicity—that of a PET drink bottle—since this allows the inputs and outputs to be shown in detail. The case studies that follow it are presented in less detail.

Bottled water

One brand of bottled water is sold in 1 liter PET bottles with polypropylene caps (similar to that in Figure 9). A bottle weighs 40 grams; the cap 1 gram. Bottles and caps are molded, filled, transported 550km from the French Alps to London, England, by 14 tonne truck, refrigerated for 2 days requiring 1 m^3 of refrigerated space at 4°C and then sold.

[2] Modern dual-cycle power stations achieve an efficiency around 40%, but averaged over all stations, some of them old, the efficiency is less.

Table 1 shows the data entered in the Eco Audit Tool.

Table 1. The inputs.

Product name: PET bottle, bill of materials.

Life: 1 year.

Step 1: Materials and manufacture: 100 units

Component name	Material	Process	Mass (kg)
Bottle, 100 units	PET	Molded	4
Cap, 100 units	PP	Molded	0.1
Dead weight (100 liters of water)	Water		100

Step 2: Transport

Stage name	Transport type	Distance (km)
Transport of filled bottles	14 tonne truck	550

Step 3: Use phase: static mode – refrigeration[i]

Energy input and output	Power rating (kw)	Usage (hr / day)	Usage (days / year)
Electric to mechanical	0.12	24	2

[i] The energy requirements for refrigeration, based on A-rated appliances are 10.5 MJ/m^3.day for refrigeration at 4^o C and 13.5 MJ/m^3.day for freezing at -5^o C. The use energy is chosen to give the value for refrigeration.

Figure 9. A 1 liter PET water bottle. The calculation is for 100 units.

What has the tool done? For ***step 1*** it retrieved from the database the energies and CO_2 profiles of the materials and the processes[3]. What it found there are *ranges* for the values. It created the (geometric) mean of the range, storing the values shown below:

Material and primary manufacturing process	Embodied energy (MJ/kg)	CO_2 footprint (kg/kg)
PET, material	84	2.3
PP, material	95	2.7
Polymer molding	6.8	0.53

It then multiplied these by the mass of each material, summing the results to give total energy and carbon.

For ***step 2*** it retrieved the energy and CO_2 profile of the selected transport mode from a look-up table, finding:

Transport type	Energy (MJ / tonne.km)	CO_2 footprint (kg CO_2 / tonne.km)
14 tonne truck	0.87	0.062

It then multiplies these by the total weight of the product and the distance traveled. If more than one transport stage is entered, the tool sums them, storing the sum. For ***step 3*** the tool retrieves an efficiency factor for the chosen energy conversion mode (here electric to mechanical because the refrigeration unit is a mechanical pump driven by an electric motor), finding in its look-up table:

Energy input and output	Efficiency factor relative to oil
Electric to mechanical	0.28

The tool uses this and the user-entered values for power and usage to calculate the energy and CO_2 profile of the use phase. For the final ***step 4*** the tool retrieved (if asked to do so) the

[3] Data are drawn from the CES EduPack Level 2 or 3 database, according to choice.

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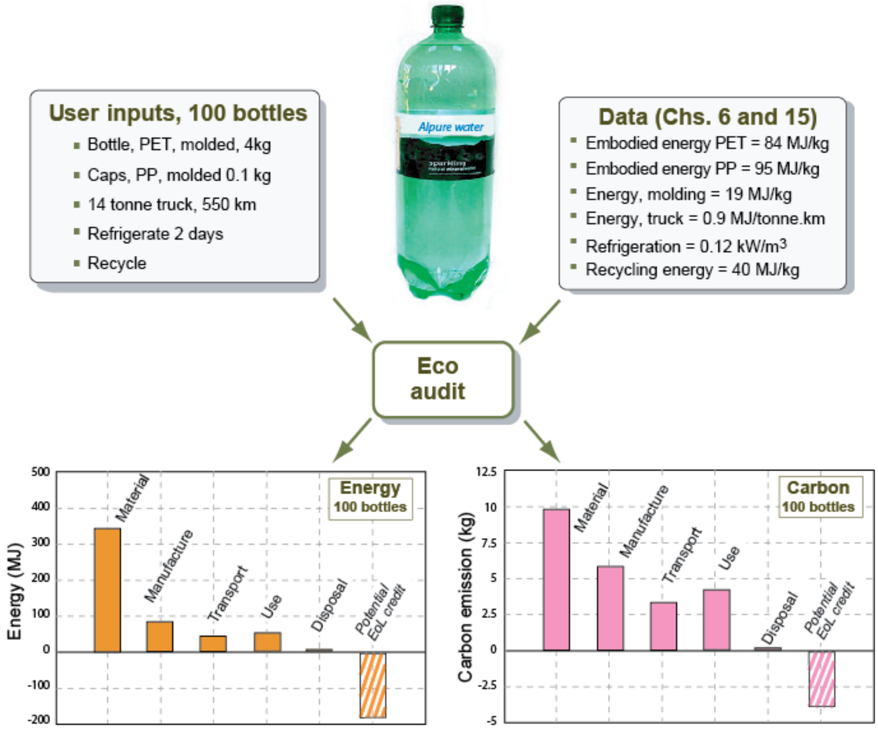

Figure 10. The energy and the carbon footprint bar-charts generated by the Eco Audit Tool for the bottles.

recycle energy and *recycle fraction in current supply* for each material and replaced the energy and CO_2 profiles for virgin materials (the default) with values for materials made with this fraction of recycled content.

Finally it created a bar chart and summary of energy or CO_2 according to user choice and a report detailing the results of each step of the calculation. The bar charts are shown in Figure 10. Table 2 shows the summary.

Table 2. PET bottle, energy, and carbon summary, 100 units.

Phase	Energy (MJ)	Energy (%)	CO_2 (kg)	CO_2 (%)
Material	344	68	9.6	48
Manufacture	36	7	3.2	16
Transport	48	10	3.4	17
Use	74.	15	3.7	19
Total	**503**	**100**	**19.9**	**100**

What do we learn from these outputs? The greatest contributions to energy consumption and CO_2 generation derive from production of the polymers used to make the bottle. (The carbon footprint of manufacture, transport, and use is proportionally larger than their energy burden, because of the inefficiencies of the energy conversions they involve). The second largest is the short, two-day, refrigeration energy. The seemingly extravagant part of the life cycle—that of transporting water, 1 kg per bottle, 550 km from the French Alps to the diner's table in London—in fact contributes 10% of the total energy and 17% of the total carbon. If genuine concern is felt about the eco impact of drinking water which has been transported over hundreds of miles, then (short of giving it up) it is the bottle that is the primary target. Could it be made thinner, using less PET? (Such bottles are 30% lighter today than they were 15 years ago). Is there a polymer that is less energy intensive than PET? Could the bottles be made reusable (and of sufficiently attractive design that people would wish to reuse them)? Could recycling of the bottles be made easier? These are design questions, the focus of the lower part of Figure 5. Methods for approaching them are detailed in references (1) and (2).

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An overall reassessment of the eco impact of the bottles should, of course, explore ways of reducing energy and carbon in all four phases of life, seeking the most efficient molding methods, the least energy intensive transport mode (32 tonne truck, barge), and minimizing the refrigeration time.

Electric jug kettle

Figure 11 shows a typical kettle. The bill of materials is listed in Table 3. The kettle is manufactured in South East Asia and transported to Europe by air freight, a distance of 11,000 km, then distributed by 24 tonne truck over a further 250 km. The power rating is 2 kW, and the volume 1.7 liters.

Table 3. Jug kettle, bill of materials. Life: 3 years.

Component	Material	Process	Mass (kg)
Kettle body	Polypropylene (PP)	Polymer molding	0.86
Heating element	Nickel-chromium alloys	Forging, rolling	0.026
Casing, heating element	Stainless steel	Forging, rolling	0.09
Cable sheath, 1 meter	Natural Rubber (NR)	Polymer molding	0.06
Cable core, 1 meter	Copper	Forging, rolling	0.015
Plug body	Phenolic	Polymer molding	0.037
Plug pins	Brass	Forging, rolling	0.03
Packaging, padding	Rigid polymer foam, MD	Polymer molding	0.015
Packaging, box	Cardboard	Construction	0.125

The kettle boils 1 liter of water in 3 minutes. It is used, on average, 3 times per day over a life of 3 years.

The bar chart in Figure 12 shows the energy breakdown delivered by the tool. Table 4 shows the summary.

Here, too, one phase of life consumes far more energy than all the others put together. Despite only using it for 9 minutes per day, the electric power (or, rather, the oil equivalent of the electric power, since conversion efficiencies are included in the calculation) accounts for 95% of the total. Improving eco performance here has to focus on this use energy—even a large change, 50% reduction, say, in any of the others makes insignificant difference. So thermal efficiency must be the target. Heat is lost through the kettle wall—selecting a polymer with lower thermal conductivity, or using a double wall with insulation in the gap, could help here—it would increase the embodied energy of the material column, but even doubling this leaves it small. A full vacuum insulation would be the ultimate answer—the water not used when the kettle is boiled would then remain close to boiling point for long enough to be useful the next time hot water is needed. The energy extravagance of air-freight makes only 3% of the total. Using sea freight instead increases the distance to 17,000 km, but reduces the transport energy per kettle to 2.8 MJ, a mere 1% of the total.

Table 4. The energy analysis of the jug kettle.

Phase	Life energy (MJ)	Energy (%)
Material	107	2.8
Manufacture	6.9	0.18
Transport	115	3.0
Use	3583	93.9
Total	**3813**	**100**

Figure 11. A 2 kW jug kettle.

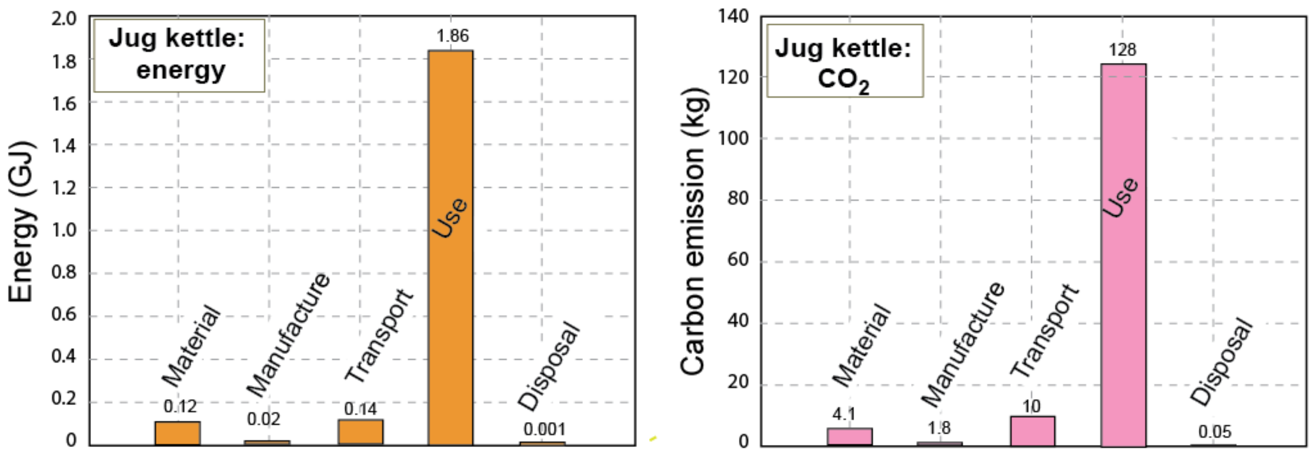

Figure 12. The energy and carbon bar-charts generated by the Eco Audit Tool for the jug kettle.

Family car—comparing material embodied energy with use energy

In this example, we use the Eco Audit Tool to compare material embodied energy with use energy. Table 5 lists one automaker's summary of the material content of a mid-sized family car (Figure 13). There is enough information here to allow a rough comparison of embodied energy with use energy using the Eco Audit Tool. We ignore manufacture and transport, focusing only on material and use. Material proxies for the vague material descriptions are given in brackets.

A plausible use-phase scenario is that of a product life of 10 years, driving 25,000 km (15,000 miles) per year, using gasoline power.

Table 5. Material content of an 1800 kg family car.

Material content	Mass (kg)
Steel (Low alloy steel)	850
Aluminum (Cast aluminum alloy)	438
Thermoplastic polymers (PU, PVC)	148
Thermosetting polymers (Polyester)	93
Elastomers (Butyl rubber)	40
Glass (Borosilicate glass)	40
Other metals (Copper)	61
Textiles (Polyester)	47

The bar chart of Figure 14 shows the comparison, plotting the data in the table below the figure (energies converted to GJ). The input data are of the most approximate nature, but it would take very large discrepancies to change the conclusion: the energy consumed in the use phase (here 84%) greatly exceeds that embodied in the materials of the vehicle.

Figure 13. A mid size family car weighting 1800kg

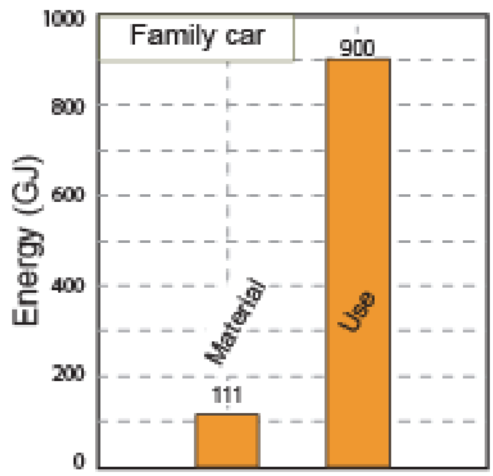

Figure 14. Eco Audit Tool output for the car detailed in Table 5, comparing embodied energy and use energy based on a life-distance of 250,000 km.

Phase	Energy (GJ)	Energy (%)
Material	162	16
Use	884	84
Total	**1046**	**100**

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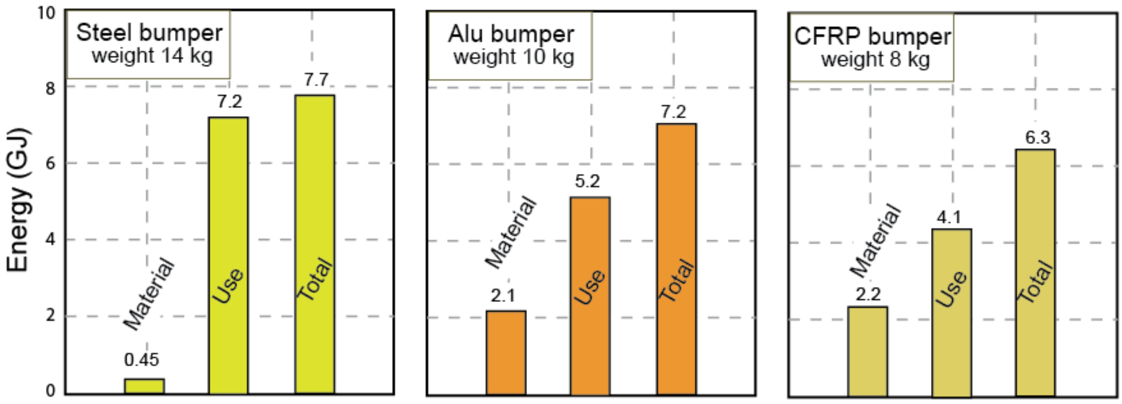

Figure 15. The comparison of the energy audits of a steel and an aluminum fender for a family car.

Auto bumpers—exploring substitution

The bumpers of a car are heavy; making them lighter can save fuel. Here we explore the replacement of a steel bumper with one of equal performance made from aluminum (Figure 16). The steel bumper weighs 14 kg; the aluminum substitute weighs 10, a reduction in weight of 28%. But the embodied energy of aluminum is much higher than that of steel. Is there a net saving?

The bar charts on the left of Figure 15 (overleaf) compare the material and use energy, assuming the use of virgin material and that the bumper is mounted on a gasoline-powered family car with a life "mileage" of 250,000 km (150,000 miles). The substitution results in a large increase in material energy and a drop in use energy. The two left-hand columns of table 6 below list the totals: the aluminum substitute wins (it has a lower total) but not by much—the break-even comes at about 200,000 km. And it costs more.

But this is not quite fair. A product like this would, if possible, incorporate recycled as well as virgin material. Clicking the box for "*Include recycle fraction*" in the tool recalculates the material energies using the *recycle content in current supply* with the *recycle energy* for this fraction[4]. The columns of the table list the new values. The aluminum bumper loses about half of its embodied energy. The steel bumper loses a little too, but not as much. The energy saving at a life of 250,000 km is considerably larger, and the break-even (found by running the tool for progressively shorter mileage until the total energy for aluminum and steel become equal) is below 100,000 km.

Table 6. Material energies and use energies for steel and aluminum bumpers.

	Virgin material		With recycle content	
Steel	**Energy (MJ)**	**Fraction (%)**	**Energy (MJ)**	**Fraction (%)**
Material: steel (14 kg)	446	6	314	4
Use: 250,000 km	7210	94	7210	96
Total	**7691**	**100**	**7567**	**100**
Aluminum				
Material: aluminum (10 kg)	2088	29	1063	17
Use: 250,000 km	5150	71	5150	83
Total	**7275**	**100**	**6250**	**100**

Figure 16. An automobile bumper.

[4] Caution is needed here: the recycle fraction of aluminum in current supply is 55%, but not all alloy grades can accept as much recycled material as this.

A portable space heater

The space heater in Figure 17 is carried as equipment on a light goods vehicle used for railway repair work. A bill of materials for the space heater is shown in Table 7 (overleaf). It burns 0.66 kg of LPG per hour, delivering an output of 9.3 kW (32,000 BTU). The air flow is driven by a 38 W electric fan. The heater weighs 7 kg. The (approximate) bill of principal materials is listed in the table. The product is manufactured in South Korea, and shipped to the US by sea freight (10,000 km) then carried by 32 tonne truck for a further 600 km to the point of sale. It is anticipated that the vehicle carrying it will travel, on average, 420 km per week, over a 3-year life, and that the heater itself will be used for 2 hours per day for 20 days per year. This is a product that uses energy during its life in two distinct ways. First there is the electricity and LPG required to make it function. Second, there is the energy penalty that arises because it increases the weight of the vehicle that carries it by 7 kg. What does the overall energy and CO_2 life profile of the heater look like?

Figure 17. A space heater powered by liquid propane gas (LPG).

The tool, at present, allows only one type of static-use energy. The power consumed by burning LPG for heat (9.3 kW) far outweighs that used to drive the small electric fan-motor (38 W), so we neglect this second contribution. It is less obvious how this static-use energy, drawn for only 40 hours per year, compares with the extra fuel-energy consumed by the vehicle because of the product weight—remembering that, as part of the equipment, it is lugged over 22,000 km per year. The Eco Audit Tool can resolve this question.

Table 7: Space heater, bill of materials. Life: 3 years.

Component	Material	Process	Mass (kg)
Heater casing	Low carbon steel	Forging, rolling	5.4
Fan	Low carbon steel	Forging, rolling	0.25
Air flow enclosure (heat shield)	Stainless steel	Forging, rolling	0.4
Motor, rotor and stator	Iron	Forging, rolling	0.13
Motor, wiring: conductors	Copper	Forging, rolling	0.08
Motor, wiring: insulation	Polyethylene	Polymer molding	0.08
Connecting hose, 2 meter	Natural Rubber (NR)	Polymer molding	0.35
Hose connector	Brass	Forging, rolling	0.09
Other components	Proxy material - polycarbonate	Proxy—polymer molding	0.22

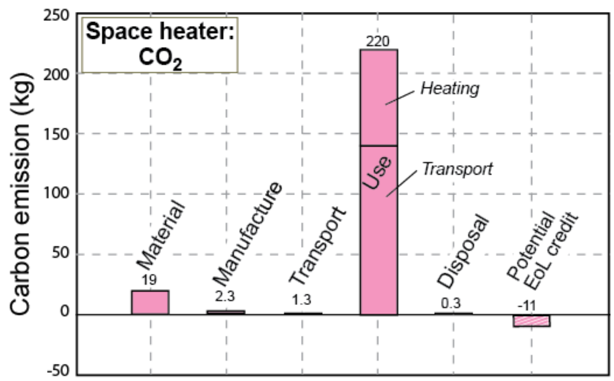

Figure 18. The energy breakdown for the space heater. The use phase dominates.

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Figure 18 shows the summary bar-chart. The use energy (as with most energy-using products) outweighs all other contributions, accounting for 94% of the total. The detailed report (Appendix) gives a breakdown of each contribution to each phase of life. One of eight tables it contains is reproduced here (Table 8)—it is a summary of the relative contributions of the two types of energy consumption during use. The consumption of energy as LPG greatly exceeds that of transport, despite the relatively short time over which it is used.

Table 8. Relative contributions of static / mobile modes.

Mode	Energy (MJ)	Energy (%)
Static	4.5×10^3	87.4
Mobile	6.4×10^2	12.6
Total	$\mathbf{5.1 \times 10^3}$	**100**

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6. Summary and conclusions

Eco aware product design has many aspects, one of which is the choice of materials. Materials are energy intensive, with high embodied energies and associated carbon footprints. Seeking to use low-energy materials might appear to be one way forward, but this can be misleading. Material choice impacts manufacturing, it influences the weight of the product and its thermal and electrical characteristics and thus the energy it consumes during use, and it influences the potential for recycling or energy recovery at the end of life. It is full-life energy that we seek to minimize.

Doing so requires a two-part strategy outlined in this White Paper. The first part is an *eco audit*: a quick, approximate assessment of the distribution of energy demand and carbon emission over life. This provides inputs to guide the second part: that of *material selection to minimize the energy and carbon* over the full life, balancing the influences of the choice over each phase of life. This White Paper describes an Eco Audit Tool that enables the first part. It is fast and easy to use, and although approximate, it delivers information with sufficient precision to enable the second part of the strategy to be performed, drawing on the same databases (available with CES EduPack). The use of the tool is illustrated with diverse case studies.

The Eco Audit Tool does not provide a full LCA, as such detail would come at a penalty of complexity and difficulty of use that would render it impractical as a design tool. The version available in CES EduPack was designed for educational use, with some further simplifications relative to the Enhanced Eco Audit Tool available for industry and research; simplicity, in teaching, is itself a valuable feature.

Granta plans to develop the tool further and welcomes ideas, criticisms, and comments from users[5].

[5] Comments can be sent on-line by using the “Feature request” option in the CES EduPack software toolbar.

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(1) Ashby, M.F. (2012) “Materials and the Environment—eco-informed material choice”, 2nd edition, Butterworth Heinemann, Oxford, UK.

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(2) Ashby, M.F. (2011) “Materials Selection in Mechanical Design”, 4th edition, Butterworth-Heinemann, Oxford, UK , Chapter 15

(4) Boustead Model 4 (1999), Boustead Consulting, Black Cottage, West Grinstead, Horsham, West Sussex, RH13 7BD, Tel: +44 1403 864 561, Fax: +44 1403 865 284, (www.boustead-consulting.co.uk)

(5) Bey, N. (2000) “The Oil Point Method: a tool for indicative environmental evaluation in material and process selection” PhD thesis, Department of Manufacturing Engineering, IPT Technical University of Denmark, Copenhagen, Denmark.

(6) Allwood, J.M., Laursen, S.E., de Rodriguez, C.M. and Bocken, N.M.P. (2006) “Well dressed? The present and future sustainability of clothing and textiles in the United Kingdom”, University of Cambridge, Institute for Manufacturing, Mill Lane, Cambridge CB2 1RX, UK ISBN 1-902546-52-0.

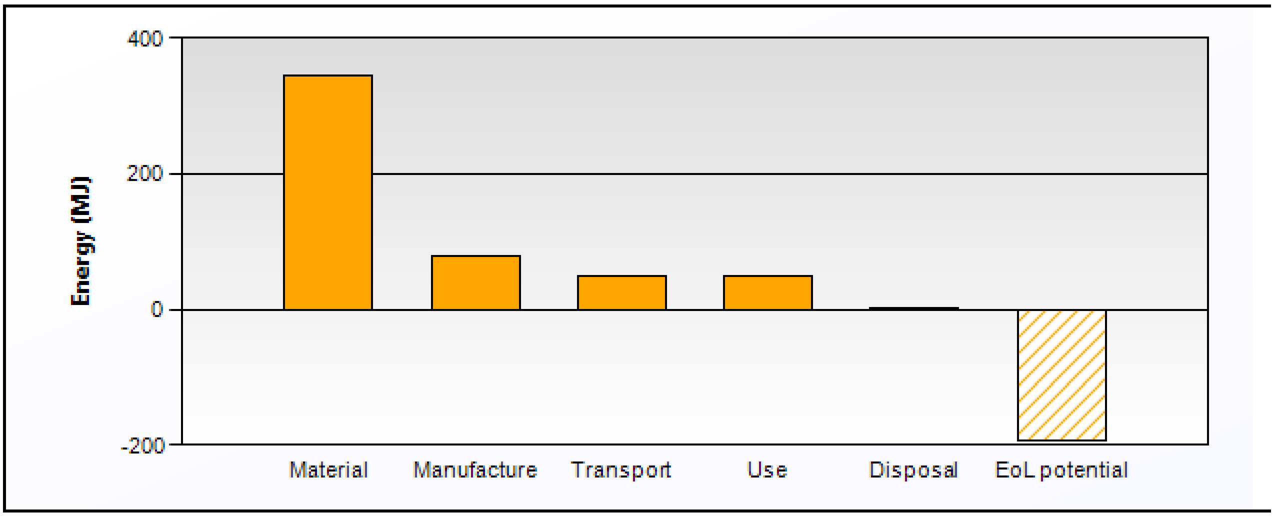
Appendix: An Eco Audit Report

On the following pages, we reproduce the Eco Audit Report generated by the Eco Audit Tool for the water bottle case study described in the text.

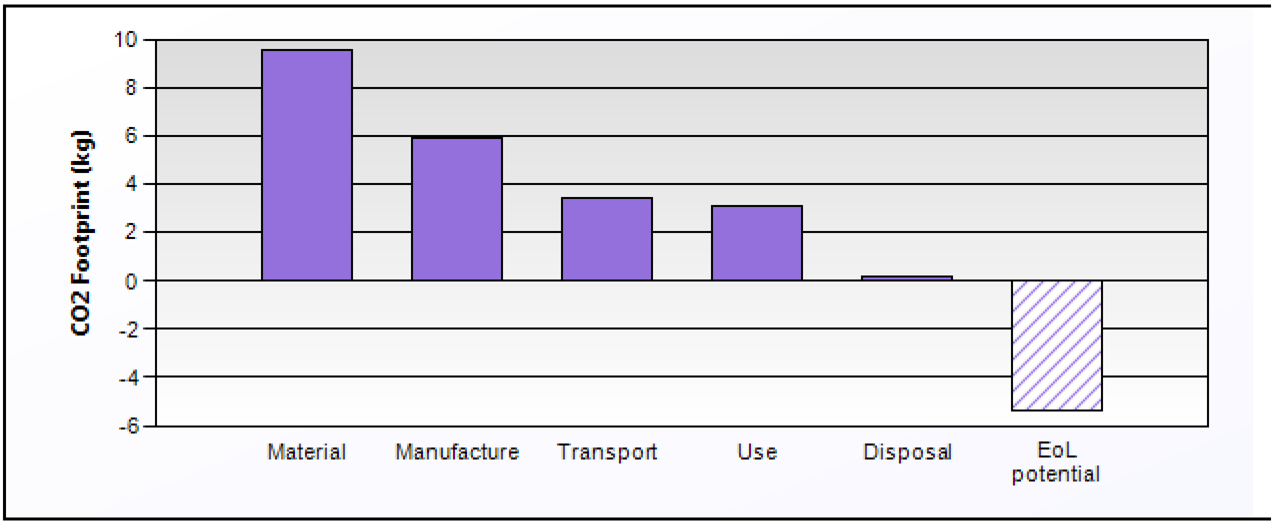
Eco Audit Report

Product Name	Bottled mineral water (100 units)
Product Life (years)	1

Energy and CO2 Footprint Summary:



Energy Details...



CO2 Details...

Phase	Energy (MJ)	Energy (%)	CO2 (kg)	CO2 (%)
Material	344	65.5	9.58	43.2
Manufacture	78.6	15.0	5.89	26.6
Transport	48.7	9.3	3.46	15.6
Use	50.8	9.7	3.05	13.8
Disposal	2.82	0.5	0.197	0.9
Total (for first life)	**525**	**100**	**22.2**	**100**
End of life potential	-194		-5.4	

Eco Audit Report

Energy Analysis

Energy and CO2 Summary

	Energy (MJ)/year
Equivalent annual environmental burden (averaged over 1 year product life):	523

Detailed breakdown of individual life phases

Material:

Energy and CO2 Summary

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass	Energy (MJ)	%
Bottles (100 units)	Polyethylene terephthalate (PET)	Virgin (0%)	4	1	4	3.3e+02	97.3
Caps(100 units)	Polypropylene (PP)	Virgin (0%)	0.1	1	0.1	9.4	2.7
Dead weight (100 litres of water)			1e+02	1	1e+02	0	0.0
Total				**3**	**1e+02**	**3.4e+02**	**100**

*Typic: Includes 'recycle fraction in current supply'

Manufacture:

Energy and CO2 Summary

Component	Process	Amount processed	Energy (MJ)	%
Bottles (100 units)	Polymer molding	4 kg	77	97.3
Caps(100 units)	Polymer molding	0.1 kg	2.1	2.7
Total			**79**	**100**

Transport:

Energy and CO2 Summary

Breakdown by transport stage Total product mass = 1e+02 kg

Stage name	Transport type	Distance (km)	Energy (MJ)	%
Filling plant - Point of sale	14 tonne truck	5.5e+02	49	100.0
Total		**5.5e+02**	**49**	**100**

Breakdown by components

Component	Component mass (kg)	Energy (MJ)	%
Bottles (100 units)	4	1.9	3.8
Caps(100 units)	0.1	0.047	0.1
Dead weight (100 litres of water)	1e+02	47	96.1
Total	**1e+02**	**49**	**100**

Use:

Energy and CO2 Summary

Static mode

Energy input and output type	Electric to mechanical (electric motors)
Use location	World
Power rating (kW)	0.12
Usage (hours per day)	24
Usage (days per year)	2
Product life (years)	1

Relative contribution of static and mobile modes

Mode	Energy (MJ)	%
Static	51	100.0
Mobile	0	
Total	**51**	**100**

Disposal:

Energy and CO2 Summary

Component	End of life option	Energy (MJ)	%
Bottles (100 units)	Recycle	2.8	99.3
Caps(100 units)	Landfill	0.02	0.7
Dead weight (100 litres of water)	None	0	0.0
Total		**2.8**	**100**

EoL potential:

Component	End of life option	Energy (MJ)	%
Bottles (100 units)	Recycle	-1.9e+02	100.0
Caps(100 units)	Landfill	0	0.0
Dead weight (100 litres of water)	None	0	0.0
Total		**-1.9e+02**	**100**

Notes:

Energy and CO2 Summary

Static Mode: Energy used to refrigerate product at point of sale

Energy required to refrigerate 100 bottles at 4°C = 0.12kW

Eco Audit Report

CO2 Footprint Analysis

Energy and CO2 Summary

	CO2 (kg)/year
Equivalent annual environmental burden (averaged over 1 year product life):	22.2

Detailed breakdown of individual life phases

Material:

Energy and CO2 Summary

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass	CO2 footprint (kg)	%
Bottles (100 units)	Polyethylene terephthalate (PET)	Virgin (0%)	4	1	4	9.3	97.2
Caps(100 units)	Polypropylene (PP)	Virgin (0%)	0.1	1	0.1	0.27	2.8
Dead weight (100 litres of water)			1e+02	1	1e+02	0	0.0
Total				**3**	**1e+02**	**9.6**	**100**

*Typic: Includes 'recycle fraction in current supply'

Manufacture:

Energy and CO2 Summary

Component	Process	Amount processed	CO2 footprint (kg)	%
Bottles (100 units)	Polymer molding	4 kg	5.7	97.3
Caps(100 units)	Polymer molding	0.1 kg	0.16	2.7
Total			**5.9**	**100**

Transport:

Energy and CO2 Summary

Breakdown by transport stage Total product mass = 1e+02 kg

Stage name	Transport type	Distance (km)	CO2 footprint (kg)	%
Filling plant - Point of sale	14 tonne truck	5.5e+02	3.5	100.0
Total		**5.5e+02**	**3.5**	**100**

Breakdown by components

Component	Component mass (kg)	CO2 footprint (kg)	%
Bottles (100 units)	4	0.13	3.8
Caps(100 units)	0.1	0.0033	0.1

Dead weight (100 litres of water)	1e+02	3.3	96.1
Total	**1e+02**	**3.5**	**100**

Use:

Energy and CO2 Summary

Static mode

Energy input and output type	Electric to mechanical (electric motors)
Use location	World
Power rating (kW)	0.12
Usage (hours per day)	24
Usage (days per year)	2
Product life (years)	1

Relative contribution of static and mobile modes

Mode	CO2 footprint (kg)	%
Static	3.1	100.0
Mobile	0	
Total	**3.1**	**100**

Disposal:

Energy and CO2 Summary

Component	End of life option	CO2 footprint (kg)	%
Bottles (100 units)	Recycle	0.2	99.3
Caps(100 units)	Landfill	0.0014	0.7
Dead weight (100 litres of water)	None	0	0.0
Total		**0.2**	**100**

EoL potential:

Component	End of life option	CO2 footprint (kg)	%
Bottles (100 units)	Recycle	-5.4	100.0
Caps(100 units)	Landfill	0	0.0
Dead weight (100 litres of water)	None	0	0.0
Total		**-5.4**	**100**

Notes:

Energy and CO2 Summary

Static Mode: Energy used to refrigerate product at point of sale
Energy required to refrigerate 100 bottles at 4°C = 0.12kW