Eco Audits and Selection Strategies for Eco Design

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ABSTRACT

This paper introduces the methods and tools that will guide in the design analysis of the role of materials and processes selection in terms of embodied energy, carbon foot print, recycle fraction, toxicity and sustainability criteria. As engineers we need to use our particular skills to guide design decisions that minimize or eliminate adverse eco impacts. The CES EduPack software is used in this study for better understanding of these issues, create material charts, perform materials and processes selection, and eco audit or life cycle analysis allowing alternative design choices to meet the engineering requirements and reduce the environmental burden. The results of the life cycle analysis of patio heater and 2 MW wind turbine are presented in this paper.

Keywords: Eco Engineering, Sustainability, Eco Audit, Engineering Design, Life Cycle Analysis

1. INTRODUCTION

The material consumption in the United States now exceeds ten tones per person per year. The average level of global consumption is about eight 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, and fossil hydrocarbons. The demand of natural resources throughout the 18th, 19th and early 20th century appeared infinitesimal. There is also a link between the population growth and resource depletion. The global resource depletion scales with the population and with per-capita consumption. Per capita consumption is growing more quickly.

The first concern is the resource consumption. Speaking globally, we consume roughly 10 billion tones of engineering materials per year. We currently consume about 9 billion tones per year of hydrocarbon fuels (oil and coal). For metals, it appears that the consumption of steel is the number one (~ 0.8 billion tones per year) followed by aluminum (10 millions tones per year). The consumption of steel exceeds, by a factor of ten all other metals combined. Polymers come next: today the combined consumption of commodity polymers polyethylene (PE), polyvinyl chloride (PVC), polypropylene (PP) and polyethylene-terephthalate, (PET) begins to approach that of steel. The really big ones, though, are the materials of the construction industry. Steel is one of these, but the consumption of wood for construction purposes exceeds that of steel even when measured in tones per year, and since it is a factor of 10 lighter, if measured in m3/year, wood totally eclipses steel. Bigger still is the consumption of concrete, which exceeds that of all other materials combined. The other big ones are asphalt (roads) and glass.

The second concern is the energy and carbon release to atmosphere caused by the production of these materials. This is calculated by multiplying the annual production by the embodied energy of the material (MJ/Kg – energy consumed to make 1 Kg of material).

New tools are needed to analyze these problems and respond to them. 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 materials 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 (material, manufacturing, use, transportation and disposal) of life, generating waste heat and solid, liquid, and gaseous emissions [1].

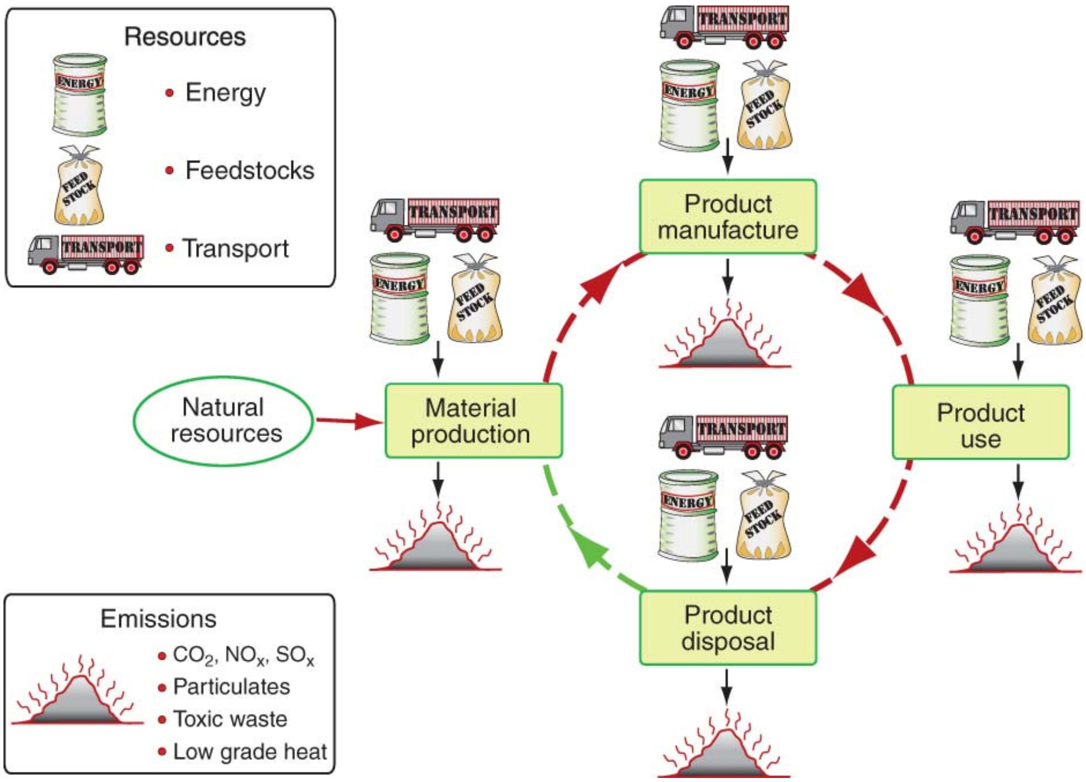


Figure 1 Material Life Cycle [1]

2. LIFE CYCLE ANALSYSI AND SELECTION STRATEGIES FOR GUIDING DESIGN

The material life cycle is shown in Figure 1. Ore and feedstock, drawn from the earth's resources, are processed to give materials. These materials are manufactured into products that are used, and, at the end of their lives, discarded, a fraction perhaps entering a recycling loop, the rest committed to incineration or land-fill. Energy and materials are consumed at each point in this cycle (phases), with an associated penalty of CO2 , SOx, NOx and other emissions, heat, and gaseous, liquid and solid waste. These are assessed by the technique of life-cycle analysis (LCA) [1-3].

2.1 The steps for life cycle analysis are:

(1) Define the goal and scope of the assessment: Why do the assessment? What is the subject and which bit (s) of its life are assessed?
(2) Compile an inventory of relevant inputs and outputs: What resources are consumed? (bill of materials) What are the emissions generated?
(3) Evaluate the potential impacts associated with those inputs and outputs
(4) Interpretation of the results of the inventory analysis and impact assessment phases in relation of the objectives of the study: What the result means? What is to be done about them?

The study examine Energy and material flows in raw material acquisition; processing and manufacturing; distribution and storage (transport, refrigeration…); use; maintenance and repair; and recycling options.

2.2 The strategy for guiding design

The first step is one of simplification, developing a tool that is approximate but retains sufficient discrimination to differentiate between alternative choices. A spectrum of levels of analysis exist, ranging from a simple ecoscreening against a list of banned or undesirable materials and processes to a full LCA, with overheads of time and cost. In between lie methods that are less rigorous; they are approximate but fast.

The second step is to select a single measure of eco-stress. On one point there is some international agreement: the Kyoto Protocol of 1997 committed the developed nations that signed it to progressively reduce carbon emissions, meaning CO2. At the national level the focus is more on reducing energy consumption, but since this and CO2 production are closely related, they are nearly equivalent. Thus there is certain logic in basing design decisions on energy consumption or CO2 generation; they carry more conviction than the use of a more obscure indicator. We shall follow this route, using energy as our measure.

The third step is to separate the contributions of the phases of life because subsequent action depends on which is the dominant one (See Figure 2). If it is that a material production, then choosing a material with low "embodied energy" is the way forward. But if it is the use phase, then choosing a material to make use less energy-intensive is the right approach, even if it has a higher embodied energy.

For selection to minimize eco-impact we must first ask: which phase of the life cycle of the product under consideration makes the largest impact on the environment? The answer guides material selection. To carry out an eco-audit we need the bill of material, shaping or manufacturing process, transportation used of the parts of the final product, the duty cycle during the use of the product, and also the eco data for the energy and CO2 footprints of materials and manufacturing process (see Figures 3 and 4).

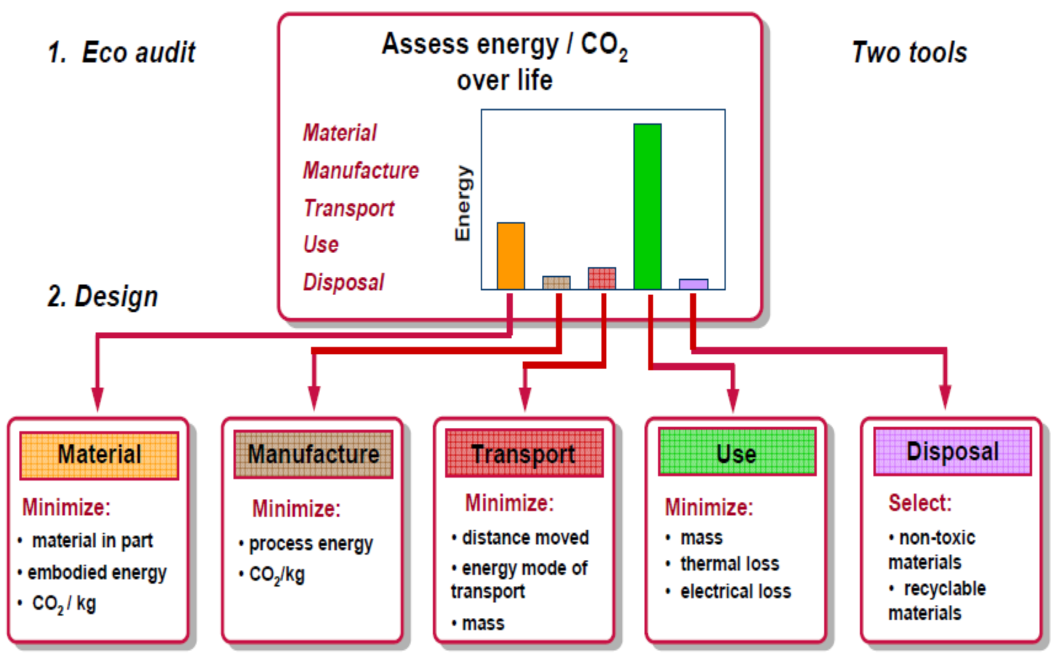


Figure 2 Eco Audit and Strategy for Guiding Eco Design [3]

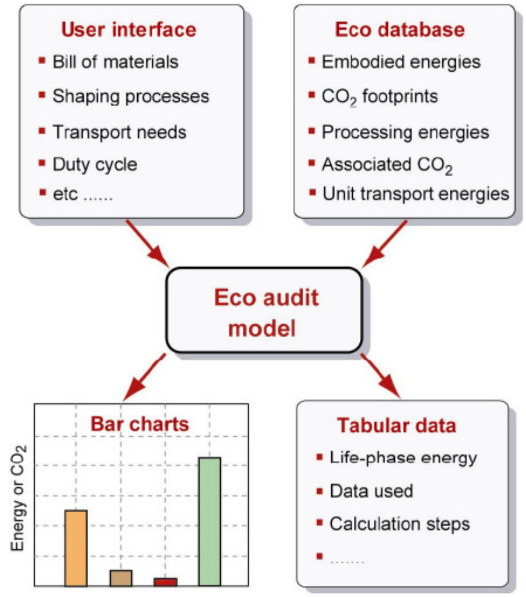


Figure 3 Energy Eco Audit Models [3]

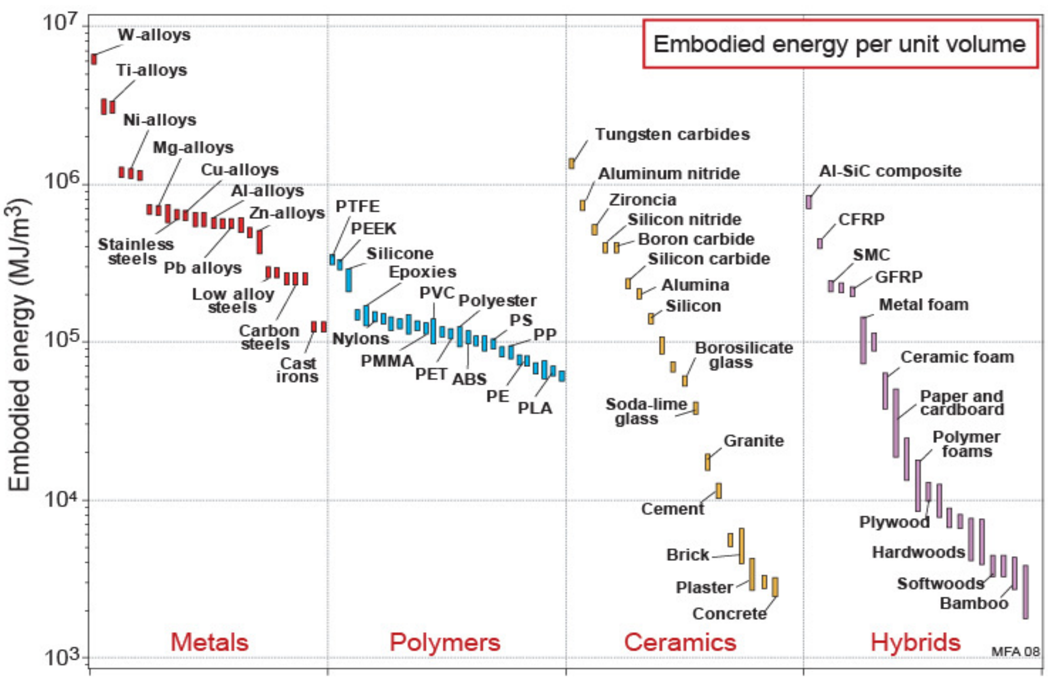


Figure 4 Embodied Energy - Primary production [3]

3. RESULTS

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. This section outlines case studies that bring out the strengths and weaknesses of the Eco Audit Tool:

3.1 Life Cycle Analysis of Patio Heater

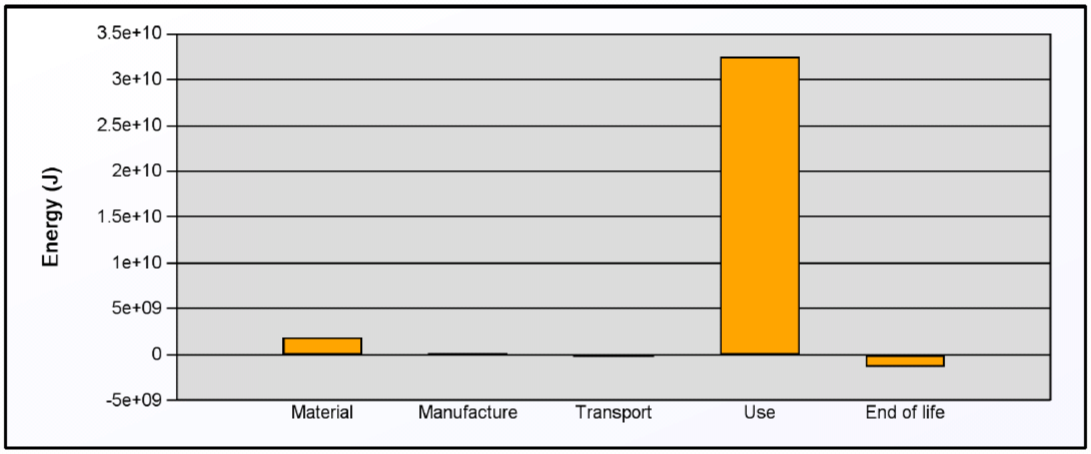
An energy and CO2 eco audits were performed for the patio heater shown in Figure 5. It is manufactured in Southeast Asia and shipped 8,000 Km to the United States, where it is sold and used. It weighs 24 kg, of which 17 kg is rolled stainless steel, 6 kg is rolled carbon steel, 0.6 kg is cast brass and 0.4 kg is unidentified injection-molded plastic (See Materials - Tables 1 and 2). During the use, it delivers 14 kW of heat ("enough to keep 8 people warm") consuming 0.9 kg of propane gas (LPG) per hour, releasing 0.059 kg of CO2 /MJ. The heater is used for 3 hours per day for 30 days per year, over 5 years, at which time the owner tires of it and takes it to the recycling depot (only 6 miles / 10 km away, so neglect the transport CO2) where the stainless steel, carbon steel and brass are sent for recycling (See end of life - Tables 1 and 2). These data are used to construct a bar-chart for energy and CO2 emission over the life of the patio heater. The table (See Figure 5) lists the energy and carbon footprints of the materials and manufacturing processes for the patio heater. The bar chart plots the totals for each phase. For the sea transport over 8000km, the energy consumed is 30.7 MJ and the CO2 released is 2.18 kg of carbon dioxide, so small as to be invisible on the bar chart. The results show that 97.9% of the energy consumed and 98.1 % of the CO2 emitted are during the use phase. The energy consumed and CO2 emitted for the material phase are respectively 5.9% and 5.2%. The results also show that 4.1% of the energy can be recovered and 3.7 % reduction of CO2 emission can be obtained by recycling the parts of the patio heater. A detailed breakdown of the energy and CO2 foot print for individual life phases (material, manufacture, transport, use, and end of life) are shown respectively in Table 1 and Table2.

3.2 Life Cycle Analysis of Wind Turbine

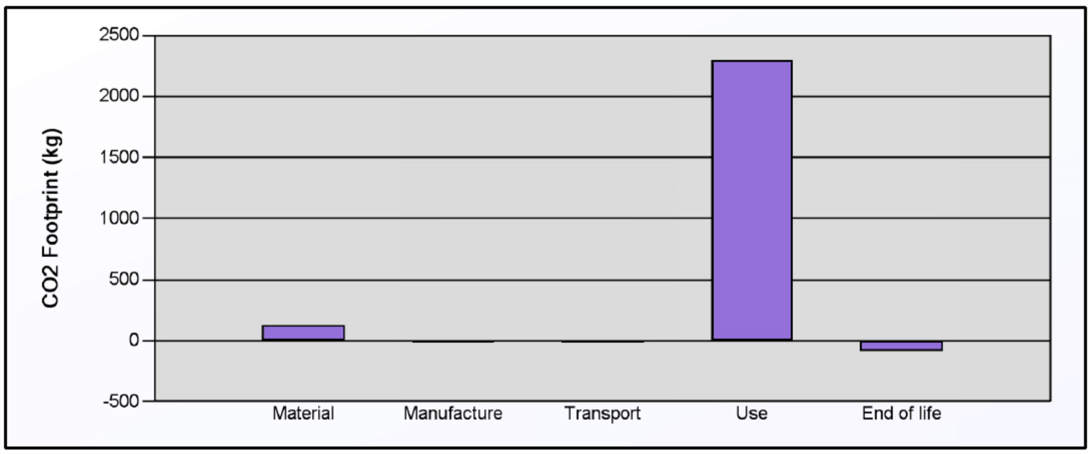
The bill of materials for a 2 MW land-based turbine [4-6] is listed in Table 3. Some energy is consumed during the turbine's life (expected to be 25 years), mostly in transport associated with maintenance. This was estimated from information on inspection and service visits in the Vestas report [4-6] and estimates of distances travelled (entered under "Static" use mode as 200 hp used for 2 hours 3 days per year). The net energy demands of each phase of life are summarized in Figure 6. The life cycle analysis was performed first without wind turbine material recycling (all the materials were sent to landfill). The second analysis was performed with wind turbine materials recycling (the wind turbine materials that can be recycled were sent to recycling at the end life of the wind turbine). Figure 6 and Table 4 show clearly the benefits of recycling the materials at the end life of the wind turbine. If all the materials are sent to landfill ate the end of life of the wind turbine, 2.18 E+011 J of energy (1.1 % of the total energy) is needed to process these materials and 13095.71 Kg of CO2 (0.9% increase of the total CO2) are released to the atmosphere at the end of life of the turbine. If the material of the wind turbine are recycled, a total energy of 6.85E+012 J representing 54.8% of the total energy is recovered at the end life of the material. A net reduction of C02 emissions by 495917.28 Kg (55.4% of the total CO2 emission) is obtained by recycling the wind turbine material.

The turbine is rated at 2 MW but it produces this power only with the right wind conditions. In a "best case" scenario the turbine runs at an average capacity factor of 40% giving an annual energy output of 7.0 x 10^6 kWhr /year. The total energy generated by the turbine over a 25 year life is 175 x 10^6 kWhr (see Table 5). The total energy generated by the turbine over 25 year life time is about 32.32 times the energy required to build and service it (5.41 10^6 kWhr) if the turbine materials are sent to landfill at the end of life of the turbine. If the materials are recycled, the total energy generated by the turbine over 25 year life time is about 50.43 times the energy required to build and service it (3.47 10^6 kWhr). With a wind turbine capacity factor of 40 %, the energy payback time is about 9.27 months if the wind turbine materials are sent to landfill at the end life of the turbine and is only 5.94 months if the materials are recycled.

Energy and CO2 Footprint Summary:



Energy Details...



CO2 Details...

Phase	Energy (J)	Energy (%)	CO2 (kg)	CO2 (%)
Material	1.94e+09	5.9	123	5.2
Manufacture	8.41e+07	0.3	6.7	0.3
Transport	3.07e+07	0.1	2.18	0.1
Use	3.24e+10	97.9	2.3e+03	98.1
End of life	-1.36e+09	-4.1	-86.2	-3.7
Total	**3.31e+10**	**100**	**2.35e+03**	**100**

Figure 5 Life Cycle Analysis of Patio Heater: Energy and CO2 Footprint Analysis

Table 1 Detailed Breakdown of individual life phases: *Energy Analysis* - Patio Heater

Material

Breakdown by component

Component	Material	Recycle content	Material Embodied Energy * (J/kg)	Total Mass (kg)	Energy (J)	%
Component 1	Stainless steel, duplex, ASTM CD-4MCu, cast	Virgin (0%)	8.1e+07	17	1.4e+09	71.1
Component 2	Stainless steel, martensitic, ASTM CA-15, cast, tempered at 315°C	Virgin (0%)	8.1e+07	6	4.9e+08	25.1
Compoent 3	Brass, CuZn10Pb3Sn2, sand-cast	Virgin (0%)	7e+07	0.6	4.2e+07	2.2
Component 4	PP (65-70% barium sulfate)	Virgin (0%)	7.7e+07	0.4	3.1e+07	1.6
Total				24	1.9e+09	100

Manufacture

Breakdown by component

Component	Process	Processing Energy (J/kg)	Total Mass (kg)	Energy (J)	%
Component 1	Forging, rolling	2.9e+06	17	5e+07	59.6
Component 2	Forging, rolling	4.1e+06	6	2.5e+07	29.5
Compoent 3	Casting	2.7e+06	0.6	1.6e+06	1.9
Component 4	Polymer molding	1.9e+07	0.4	7.6e+06	9.0
Total			24	8.4e+07	100

Transport

Breakdown by transport stage Total product mass = 24 kg

Stage Name	Transport Type	Transport Energy (J/kg.m)	Distance (m)	Energy (J)	%
	Sea freight	0.16	8e+06	3.1e+07	100.0
Total			8e+06	3.1e+07	100

Breakdown by components Total transport distance = 8e+06 m

Component	Total Mass (kg)	Energy (J)	%
Component 1	17	2.2e+07	70.8
Component 2	6	7.7e+06	25.0
Compoent 3	0.6	7.7e+05	2.5
Component 4	0.4	5.1e+05	1.7
Total	24	3.1e+07	100

Use

Relative contribution of static and mobile modes

Mode	Energy (J)	%
Static	3.2e+10	100.0
Mobile	0	
Total	3.2e+10	100

Static Mode

Energy Input and Output Type	Fossil fuel to thermal, vented system
Product Efficiency	0.7
Use Location	United States
Energy Equivalence, source (J/J)	1
Power Rating (kW)	14
Usage (hours per day)	3
Usage (days per year)	30
Product Life (years)	5
Total Life Usage (hours)	4.5e+02

End of Life

Relative contributions of end of life options

Component	End of Life Route	Collection Energy (J/kg)	Potential End of Life 'Saving' (J/kg)	Total Mass (kg)	Total EoL Energy (J)	%
Component 1	Recycle	7e+05	-5.8e+07	17	-9.8e+08	71.7
Component 2	Recycle	7e+05	-5.8e+07	6	-3.5e+08	25.3
Compoent 3	Recycle	7e+05	-5e+07	0.6	-2.9e+07	2.5
Component 4	Landfill	2e+05	0	0.4	8e+04	0.5
Total				24	-1.4e+09	100

Table 2 Detailed Breakdown of individual life phases: *CO2 Foot Print* - Patio Heater

Material

Breakdown by component

Component	Material	Recycle content	Material CO2 Footprint * (kg/kg)	Total Mass (kg)	CO2 Footprint (kg)	%
Component 1	Stainless steel, duplex, ASTM CD-4MCu, cast	Virgin (0%)	5.1	17	87	70.5
Component 2	Stainless steel, martensitic, ASTM CA-15, cast, tempered at 315°C	Virgin (0%)	5.1	6	31	24.9
Compoent 3	Brass, CuZn10Pb3Sn2, sand-cast	Virgin (0%)	6.2	0.6	3.7	3.0
Component 4	PP (65-70% barium sulfate)	Virgin (0%)	4.7	0.4	1.9	1.5
Total				24	1.2e+02	100

Manufacture

Breakdown by component

Component	Process	Processing CO2 (kg/kg)	Total Mass (kg)	CO2 Footprint (kg)	%
Component 1	Forging, rolling	0.24	17	4	59.8
Component 2	Forging, rolling	0.33	6	2	29.6
Compoent 3	Casting	0.16	0.6	0.097	1.4
Component 4	Polymer molding	1.5	0.4	0.61	9.1
Total			24	6.7	100

Transport

Breakdown by transport stage Total product mass = 24 kg

Stage Name	Transport Type	Transport Energy (J/kg.m)	CO2 Footprint, source (kg/J)	Distance (m)	CO2 Footprint (kg)	%
	Sea freight	0.16	7.1e-08	8e+06	2.2	100.0
Total				8e+06	2.2	100

Breakdown by components Total transport distance = 8e+06 m

Component	Total Mass (kg)	CO2 Footprint (kg)	%
Component 1	17	1.5	70.8
Component 2	6	0.55	25.0
Compoent 3	0.6	0.055	2.5
Component 4	0.4	0.036	1.7
Total	24	2.2	100

Use

Relative contribution of static and mobile modes

Mode	CO2 Footprint (kg)	%
Static	2.3e+03	100.0
Mobile	0	
Total	2.3e+03	100

Static Mode

Energy Input and Output Type	Fossil fuel to thermal, vented system
Product Efficiency	0.7
Use Location	United States
CO2 Footprint, source (kg/J)	7.1e-08
Power Rating (kW)	14
Usage (hours per day)	3
Usage (days per year)	30
Product Life (years)	5
Total Life Usage (hours)	4.5e+02

End of Life

Relative contributions of end of life options

Component	End of Life Route	Collection CO2 (kg/kg)	Potential End of Life 'Saving' (kg/kg)	Total Mass (kg)	Total EoL CO2 (kg)	%
Component 1	Recycle	0.042	-3.7	17	-62	71.7
Component 2	Recycle	0.042	-3.7	6	-22	25.3
Compoent 3	Recycle	0.042	-4.6	0.6	-2.7	2.5
Component 4	Landfill	0.012	0	0.4	0.0048	0.5
Total				24	-86	100

Table 3: Bill of Materials for the 2 MW Wind Turbines

Component	Material	Total Mass (kg)
Tower structure	Low carbon steel	164000.000
Tower, Cathodic Protection	Zinc alloys	203.000
Nacelle, gears	Stainless steel	19000.000
Nacelle, generator core	Cast iron, gray	9000.000
Nacelle, generator conductors	Copper	1000.000
Nacelle, transformer core	Cast iron, gray	6000.000
Nacelle, transformer conductors	Copper	2000.000
Nacelle, transformer conductors	Aluminum alloys	1700.000
Nacelle, cover	GFRP, epoxy matrix (isotropic)	4000.000
Nacelle, main shaft	Cast iron, ductile (nodular)	12000.000
Nacelle, other forged components	Stainless steel	3000.000
Nacelle, other cast components	Cast iron, ductile (nodular)	4000.000
Rotor, blades	CFRP, epoxy matrix (isotropic)	24500.000
Rotor, iron components	Cast iron, ductile (nodular)	2000.000
Rotor, spinner	GFRP, epoxy matrix (isotropic)	3000.000
Rotor, spinner	Cast iron, ductile (nodular)	2200.000
Foundations, pile & platform	Concrete	805000.000
Foundations, steel	Low carbon steel	27000.000
Transmission, conductors	Copper	254.000
Transmission, conductors	Aluminum alloys	72.000
Transmission, insulation	Polyethylene (PE)	1380.000
Total		**1.091E+006**

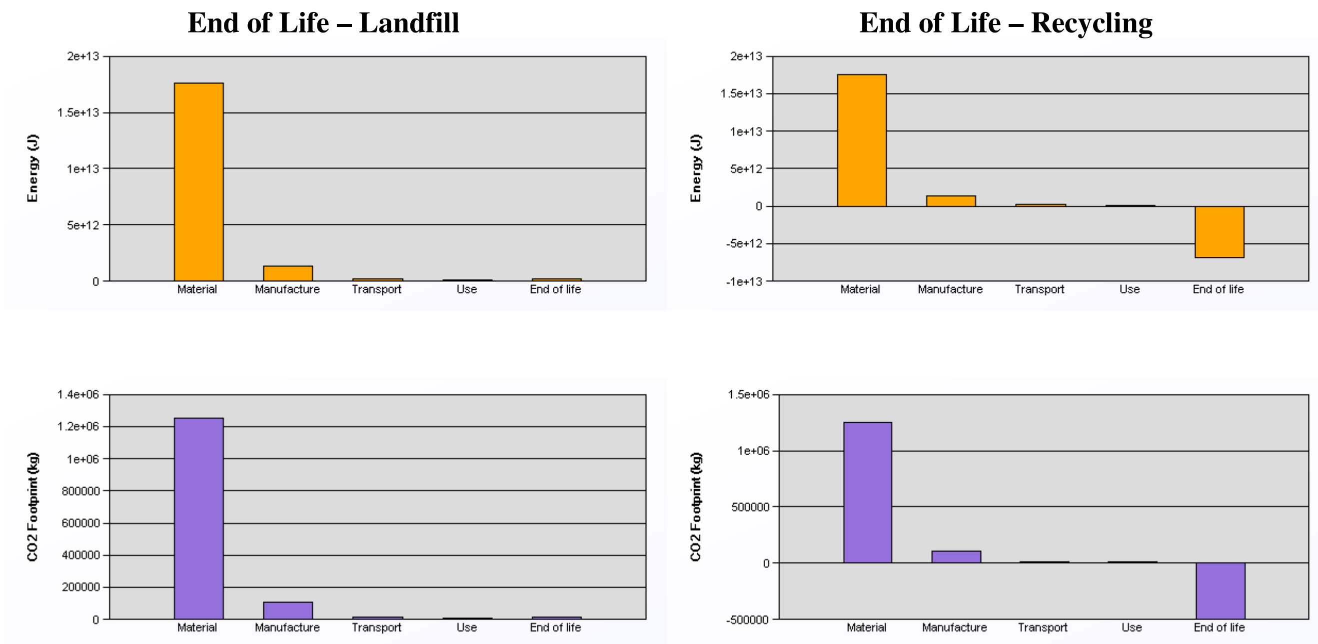


Figure 6 Life Cycle Analysis of Wind Turbine - With and Without Wind Turbine Material Recycling

Table 4 Energy and CO2 Footprint Summary – Wind Turbine

	End of Life – Landfill		**End of Life – Recycling**	
Phase	**Energy (J)**	**CO2 (kg)**	**Energy (J)**	**CO2 (kg)**
Material	1.7594E+013	1.2546E+006	1.7594E+013	1.2546E+006
Manufacture	1.3593E+012	107669.7209	1.3593E+012	107669.7209
Transport	2.4336E+011	17278.6954	2.4336E+011	17278.6954
Use	1.6778E+011	11912.5577	1.6778E+011	11912.5577
End of life	2.1826E+011	13095.7080	-6.8512E+012	-495917.2797
Total	**1.9583E+013**	**1.4045E+006**	**1.2513E+013**	**895503.8906**

Table 5 Construction Energy, Wind Turbine Energy Output and Energy Pay Back Time

	End of life landfill	**End of life Recycling**
Total Construction Energy (J)	$1.95\ 10^{13}$	$1.25\ 10^{13}$
TCE - Total Construction Energy (kWhr)	$5.41\ 10^{6}$	$3.47\ 10^{6}$
AEO - Annual Energy Output with 40% capacity factor (kWhr/year)	$7.0\ 10^{6}$	$7.0\ 10^{6}$
TE - Total Energy for the 25 years life of the turbine (kWhr)	$175\ 10^{6}$	$175\ 10^{6}$
TE/TCE - Total Energy Generated by the Turbine / Total Construction Energy	32.32	50.43
EPBT = TCE/AEO Energy Pay back Time (months)	9.27	5.94

4. CONCLUSIONS

In eco aware product design, the materials are energy intensive with high embodies energy and carbon foot print, the material choice impacts the energy and CO2 for the manufacturing process, the material impacts the weight of the product and its thermal and electric characteristics and the energy it consumes during the use; and the material choice also impacts the potential for recycling or energy recovery at the end of life. The eco aware product design has two-part strategy: (1) Eco Audit: quick and approximate assessment of the distribution of energy demand and carbon emission over a product's life; and (2) material selection to minimize the energy and carbon over the full life, balancing the influence of the choice over each phase of the life (selection strategies and eco informed material selection). The results of two case studies (patio heater and wind turbine) are presented in this paper. The results show the problem with the energy consumed and carbon foot print for the patio heater was during the use of the heater but for the 2 MW wind turbine was for the material phase.

REFERENCES

[1] Ashby, M.F. Shercliff, H. and Cebon, D. (2007), "Materials: engineering, science, processing and design", Butterworth Heinemann, Oxford UK, Chapter 20.

[2] Ashby, M.F. (2005) "Materials Selection in Mechanical Design", 3rd edition, Butterworth- Heinemann, Oxford, UK, Chapter 16.

[3] Granta Design Limited, Cambridge, (2009) (www.grantadesign.com), CES EduPack User Guide

[4] Elsam Engineering A/S, (2004) "Life Cycle Assessment of Offshore and Onshore Sited Wind Farms", Report by Vestas Wind Systems A/S of the Danish Elsam Engineering

[5] Nordex N90 Technical Description, Nordex Energy (2004)

[6] Vestas (2005) "Life cycle assessment of offshore and onshore sited wind turbines" Vestas Wind Systems A/S, Alsvij 21, 8900 Randus, Denmark (www.vestas.com)

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