CE
Solutions for environment, economy and technology

Oude Delft 180
2611 HH Delft
The Netherlands
tel: +31 15 2 150 150
fax: +31 15 2 150 151
e-mail: ce@ce.nl
website: www.ce.nl
KvK 27251086

Environmental profiles of motors and transformers

Report

Delft, March 2003

Authors: H.J. Croezen
O.S.F. Bello

Publication data

H.J. Croezen, O.S.F. Bello
Environmental profiles of motors and transformers
Delft, CE, 2003

Copper / Industry / Electric motors / LCA / Environmental impact

Publication code: 03.5423.07/e

CE publications are distributed by:
CE
Oude Delft 180
2611 HH Delft
The Netherlands
Tel: 015-2150150
Fax: 015-2150151
E-mail: publicatie@ce.nl

This study was commissioned by the European Copper Institute.

For further information, please contact project manager H.J. Croezen.

CE
Solutions for environment, economy and technology

CE is an independent research and consultancy agency specialised in developing structural and innovative solutions to environmental problems. CE solutions are characterised in being politically feasible, technically sound, economically prudent and socially equitable.

CE has five divisions engaged in the following fields:
- economics
- energy
- industry
- materials
- transport

Each of these divisions has a publications list, available from CE free of charge: tel. +31 15 - 2150150. The most recent information can be found at CE's website: www.ce.nl

Contents

Summary

At the request of the ECI, the European Copper Institute, CE has performed a abridged Life Cycle Assessment of electric motors and transformers. The aim of this LCA was to compare the additional environmental impact associated with extra materials usage with the impact avoided through reduced electrical power consumption.

The results of our study show that the principal life-cycle environmental impact of both motors and transformers is the greenhouse effect, i.e. climate change. Operational power consumption contributes most to climate change, which means that any improvement of motor efficiency will substantially benefit the environmental profile of the equipment. In this regard, then, wise use of more metal in motor manufacture may provide scope for achieving environmental performance.

1 Introduction

1.1 Aim, scope and background

At the request of the European Copper Institute (ECI) CE has performed an abridged Life Cycle Assessment of electric motors and transformers. This 'mini LCA' follows on from an earlier CE study on copper, commissioned by Copper Benelux. The same methodology was used in both studies to compute the environmental profile: rather than using the classification factors developed by CML, we quantified environmental performance on the basis of shadow prices.

Electric motor efficiency ranges from about 60% for small, relatively inefficient units to 97% for high-efficiency, industrial-scale plant. Load losses are governed by various factors, including the mass of materials embodied in the unit, and can be reduced by using more, and superior, materials in manufacture.

On average, about 35% of overall load losses can be attributed to the electrical resistance of the copper windings, a figure that can be improved by using thicker gauge wire. ECI has calculated that using an additional 25,000 tonnes of copper a year in industrial motor windings would save some 30 TWh_e of electrical power a year in the EU. Industrial power consumption for this end currently stands at 575 TWh_e/y in the EU.

Cutting load losses would lead to a corresponding decrease in electrical power demand, thus avoiding the environmental impact associated with generation. However, these gains will be offset to some degree by the extra environmental burden embodied in the extra manufacturing materials. The aim of the present 'mini-LCA', then, was to estimate the environmental gains that might, on balance, thus be achieved.

As a preliminary step in this comparison, CE had already established specific indices for the environmental impacts associated with materials production and power generation. These are presented and discussed in the next section, which also reviews the shadow prices taken for motor and transformer performance.

Section 3 reports the calculated environmental impacts of the various types of motor considered, looking first at materials (3.1) and then at energy (3.2). In Section 4 these material and energy data are aggregated to a single environmental profile for each type of motor. The results are then discussed and conclusions presented.

2 Shadow prices

2.1 Impact factors for materials and energy use

The working part of a motor or transformer is fabricated mainly from three metals: aluminium, steel and copper. While other materials such as insulating coatings, cast iron and oil are also involved, the quantities in question are roughly the same for all types of motor, ‘standard’ as well as ‘high-efficiency’; we therefore disregarded these in our analysis.

In everyday practice, the three cited metals are produced from both primary resources and scrap. However, any *additional* demand arising from improved motor design would have to be met by additional primary resources. At the end of the new motor’s operational lifetime, on the other hand, there would be more scrap available for recycling and this figure has also been included in our calculations.

As the basic point of departure for this study’s analysis we have therefore taken the environmental impact attributable to primary metals production. The impact factors used in this study are shown in Table 1.

Table 1 Impact factors for materials and energy use

Output of 1,000 kg product	Climate change GWP100 (kg CO_2-eq.)	Acidification (kg SO_2-eq.)	Toxics dispersion (kg polluted env.)
Materials			
Extruded aluminium	12,488	84	6.68E+04
Steel blast furnace route, 20% recycling	2,770	7	7.58E+02
Copper, EU average for wire rod	3,966	261	9.88E+12
Electrical power generation*			
Netherlands			
(per GJe)	168	0.16	
(per kWhe)	0.6	5.7E-04	
EU			
(per GJe)	111	0.45	
(per kWhe)	0.4	0.16E-04	
Shadow price (€/kg emission)	0.04	4	2.73E-10

* EcoFYS, 2001

The figures for aluminium have been taken from |1| and are averages for the European aluminium industry. For steel we have based ourselves on the data reported in |2|, which are for conventionally rolled steel, not the amorphous or oriented steel normally used in motors. The manufacturing process differs to some extent in the two cases, but unfortunately more specific data are not available. In the case of copper we computed an average figure for the impact attributable to the primary copper used in European-produced wire rod. Background data were derived from the ‘best case, worst case’ analysis carried out by CE.

Atmospheric emissions of NO_x contribute to acidification and have been incorporated in the impact factors for power production. The fine particulate emissions arising during power generation have not been included here, for their contribution to the third environmental theme considered here, toxics dispersion, is negligible compared with that of the manufacturing materials. The slag and ashes produced per kWh power generated do not contribute to the environmental themes considered in this study and have therefore also been excluded from the analysis.

Figures for the environmental impacts of power generation were likewise taken from CE's 'best case, worst case' analysis.

2.2 Other environmental themes

Besides *climate change*, *acidification* and *toxics dispersion,* LCAs also generally cover the following themes:
- abiotic depletion;
- ozone layer depletion;
- photochemical oxidation;
- eutrophication.

We know of no published shadow prices for these themes, however, nor have we have made any attempt to calculate such prices ourselves. Fortunately, these environmental themes are not that relevant for a study concerned with power consumption and metals use, as has been demonstrated in earlier studies using the standard CML classification factors.

3 Environmental performance

3.1 Environmental impact per kg material

The materials embodied in an electric motor are each associated with a specific environmental burden, and any additional materials usage to improve motor efficiency generally leads to an increase of that burden.

The basic impact factors used in this study for the three materials of interest are shown in Table 2.

Table 2 Basic impact factors, materials

Materials	Climate change ($kg\ CO_2$-eq)	Acidification ($kg\ SO_2$-eq)	Toxics dispersion (kg polluted env't)
Al (1 kg)	12.5	84 E-03	66.8
Fe (1 kg)	2.8	7 E-03	0.758
Cu (1 kg)	4.0	261 E-03	9.88E+9

3.1.1 15 kW motors

For this category of motor the following impact factors were used.

Table 3 Impact factors, 15 kW motors

		type 1	type 2	type 3	type 4	
15 kW	**Cu (kg)**	**8.1**	**8.3**	**9.2**	**10.3**	Cu-ETP
	Al (kg)	**3.1**	**3.1**	**3.3**	**3.3**	Casting
	Fe (kg)	**72.4**	**72.4**	**104**	**104**	Rolled silicon steel 0.3-0.5 mm
Efficiency		88.8%	89.4%	90.6%	91.8%	
running hours		3,000	3,000	3,000	3,000	
energy (MWh/year)		50.7	50.3	49.7	49.0	
lifetime (years)		15	15	15	15	
energy (MWh - lifetime)		760.1	755.0	745.0	735.3	

Source: University L'Aquila, Prof. Parasiliti.

The environmental impacts associated with the Cu, Al and Fe used in this type of motor are shown in Table 4.

Table 4 Environmental impacts, materials, 15 kW motors

Motors		Climate change ($kg\ CO_2$-eq.)	Acidification ($kg\ SO_2$-eq.)	Toxics dispersion (kg 1,4-dichlorobenzene-eq.)
15 kW				
	type 1	271.39	2.88	8.00E+10
	type 2	272.18	2.93	8.20E+10
	type 3	365.78	3.41	9.09E+10
	type 4	370.14	3.69	1.02E+11

3.1.2 22 kW motors

For this category of motor the following impact factors were used.

Table 5 Impact factors, 22 kW motors

		type 1	type 2	Type 3	type 4	
22 kW	**Cu (kg)**	**8.8**	**10.5**	**12.9**	**13.9**	Cu-ETP
	Al (kg)	**3.46**	**3.46**	**3.5**	**4**	Casting
	Fe (kg)	**108**	**108**	**108**	**108**	Rolled silicon steel 0.3-0.5 mm
Efficiency		89.5%	90.5%	91.8%	92.6%	
running hours		4.000	4.000	4.000	4.000	
energy (MWh/year)		98.3	97.2	95.9	95.0	
lifetime (years)		15	15	15	15	
energy (MWh - lifetime)		1,474.9	1,458.6	1,437.9	1,425.5	

Source: University L'Aquila, Prof. Parasiliti.

The environmental impacts of the Cu, Al and Fe used in this motor are shown in Table 6.

Table 6 Environmental impacts, materials, 22 kW motors

Motors	Climate change (kg CO_2-eq.)	Acidification (kg SO_2-eq.)	Toxics dispersion (kg 1,4-dichlorobenzene-eq.)
22 kW			
type 1	377.27	3.34	8.69^{E}+10
type 2	384.01	3.79	1.04^{E}+11
type 3	394.03	4.42	1.27^{E}+11
type 4	404.24	4.72	1.37^{E}+11

3.1.3 400 kVA transformers

For these transformers the following factors were used.

Table 7 Impact factors, 400 kVA transformers

		AA Type 1	**CC Type 2**	**C-Amorf Type 3**	
400 kVA	**Cu (kg)**	**203**	**350**	**450**	Cu-ETP
	Fe (kg)	**435**	**450**	**600**	Rolled silicon steel 0.3-0.5 mm
Efficiency		98.4%	98.6%	99.4%	
running hours		8760	8760	8760	
energy (MWh/year)		3561.0	3552.3	3525.2	
lifetime (years)		30	30	30	
energy (MWh - lifetime)		106,829.3	106,569.3	105,754.5	

Source: THERMIE final report STR/1678/98/BE

Table 8 shows the environmental impacts of the three metals for this type of transformer.

Table 8 Environment impacts, materials, 400 kVA transformers

Transformer		Climate change (kg CO_2-eq.)	Adicification (kg SO_2-eq.)	Toxics dispersion (kg 1,4-dichlorobenzene-eq.)
type				
	AA	2,010.05	56.03	2.01E+12
	CC	2,634.60	94.50	3.46E+12
	C-Amorph	3,446.70	121.65	4.45E+12

3.1.4 1,600 kVA transformers

For these transformers the following factors were used.

Table 9 Impact factors, 1600 kVA transformers

1600 kVA	**Cu (kg)** **Fe (kg)**	**505** **1100**	**725** **1200**	**1225** **1550**	Cu-ETP Rolled silicon steel 0.3-0.5 mm
Efficiency		98.5%	98.9%	99.5%	
running hours		8.760	8.760	8.760	
energy (MWh/year)		14,228.0	14,166.2	14,093.5	
lifetime (years)		30	30	30	
energy (MWh - lifetime)		426,839.9	424,984.8	422,805.4	

Source: THERMIE final report STR/1678/98/BE

The environmental impacts of the Cu, Al and Fe used in these transformers are shown in Table 10.

Table 10 Environmental impacts, materials, 1,600 kVA transformers

Transformers		Climate change (kg CO_2-eq.)	Acidification (kg SO_2-eq.)	Toxics dispersion (kg 1,4-dichlorobenzene-eq.)
1600 kVA				
	type 1	5,049.83	139.51	4.99E+12
	type 2	6,199.35	197.63	7.16E+12
	type 3	9,151.85	330.58	1.21E+13

3.2 Environmental impact per kWh power consumption

Environmental impact per kWh electrical input is governed by motor characteristics and the reference scenario used for generating park. Two reference parks were considered in this study: Dutch and EU. For the various categories of motor considered, the environmental performance associated with lifetime power consumption is reported for both.

Contrary to the situation for materials, above, in the case of energy use it is only the themes of climate change and acidification that make a significant contribution to environmental performance.

3.2.1 15 kW motors

Table 11 Environmental impacts, power consumption, 15 kW motors

	Dutch park		European park	
	Climate change (kg CO_2-eq.)	Acidification (kg SO_2-eq.)	Climate change (kg CO_2-eq.)	Acidification (kg SO_2-eq.)
15 kW				
type 1	459,729.73	437.84	304,054.05	1,244.50
type 2	456,644.30	434.90	302,013.42	1,236.15
Type 3	450,596.03	429.14	298,013.25	1,219.78
Type 4	444,705.88	423.53	294,117.65	1,203.83

3.2.2 22 kW motors

Table 12 Environmental impacts, power consumption, 22 kW motors

	Dutch park		European park	
	Climate change (kg CO_2-eq)	Acidification (kg SO_2-eq)	Climate change (kg CO_2-eq)	Acidification (kg SO_2-eq)
22 kW				
type 1	891,995.53	849.52	589,944.13	2,414.66
type 2	882,139.23	840.13	583,425.41	2,387.97
type 3	869,647.06	828.24	575,163.40	2,354.16
type 4	862,133.91	821.08	570,194.38	2,333.82

3.2.3 400 kVA transformers

Table 13 Environmental impacts, power consumption, 400 kVA transformers

	Dutch park		European park	
	Climate change (kg CO_2-eq.)	Acidification (kg SO_2-eq.)	Climate change (kg CO_2-eq.)	Acidification (kg SO_2-eq.)
400 kVA				
AA	6.46E+07	61,533.66	4.27E+07	174,901.87
CC	6.45E+07	61,383.94	4.26E+07	174,476.32
C-Amorph	6.40E+07	60,914.61	4.23E+07	173,142.30

3.2.4 1,600 kVA transformers

Table 14 Environmental impacts, energy consumption, 1600 kVA transformers

		Dutch park		European park	
		Climate change ($kg\ CO_2$-eq)	Acidification ($kg\ SO_2$-eq)	Climate change ($kg\ CO_2$-eq)	Acidification ($kg\ SO_2$-eq)
1,600 kVA					
	type 1	2.58E+08	245,859.79	1.71E+08	698,826.28
	type 2	2.57E+08	244,791.27	1.70E+08	695,789.13
	type 3	2.56E+08	243,535.93	1.69E+08	692,220.98

4 Results and conclusions

This section presents, for the various types of motor and transformer, the aggregate environmental impact associated with materials and energy use, or 'lifetime environmental profile', as computed using the impact factors cited in Section 3 and the shadow prices of Section 2. Based on these results, we draw some conclusions on environmental policy themes of relevance for motors and transformers.

4.1 Lifetime environmental profile: motors

4.1.1 15 kW motors

Table 15 Lifetime environmental profile, 15 kW motors

Dutch energy model 15 kW	Climate change (euro / lifetime)	Acidification (euro / lifetime)	Toxics dispersion (euro / lifetime)	**Total (euro / lifetime)**	**Gain rel. to type 1 (euro / lifetime)**
type 1	18,400.04	1,762.88	21.85	**20,185**	**--**
type 2	18,276.66	1,751.33	22.39	**20,050**	**-134**
type 3	18,038.47	1,730.18	24.81	**19,793**	**-391**
type 4	17,803.04	1,708.89	27.78	**19,540**	**-645**

EU energy model 15 kW	Climate change (euro / lifetime)	Acidification (euro / lifetime)	Toxics dispersion (euro / lifetime)	**Total (euro / lifetime)**	Gain rel. to type 1 (euro / lifetime)
type 1	12,173.02	4,989.53	21.85	17,184	--
type 2	12,091.42	4,956.33	22.39	17,070	-114
type 3	11,935.16	4,892.73	24.81	16,853	-332
type 4	11,779.51	4,830.10	27.78	16,637	-547

4.1.2 22 kW motors

Table 16 Lifetime environmental profile, 22 kW motors

Dutch energy model 22 kW	Climate change (euro / lifetime)	Acidification (euro / lifetime)	Toxics dispersion (euro / lifetime)	**Total (euro / lifetime)**	Gain rel. to type 1 (euro / lifetime)
type 1	35,694.91	3,411.45	23.74	**39,130**	--
type 2	35,300.93	3,375.68	28.32	**38,705**	**-425**
type 3	34,801.64	3,330.61	34.79	**38,167**	**-963**
type 4	34,501.53	3,303.20	37.49	**37,842**	**-1,288**

EU energy model 22 kW	Climate change (euro / lifetime)	Acidification (euro / lifetime)	Toxics dispersion (euro / lifetime)	**Total (euro / lifetime)**	Gain rel. to type 1 (euro / lifetime)
type 1	23,612.86	9,671.99	23.74	33,309	--
type 2	23,352.38	9,567.04	28.32	32,948	**-361**
type 3	23,022.30	9,434.30	34.79	32,491	**-817**
type 4	22,823.94	9,354.16	37.49	32,216	**-1,093**

4.2 Lifetime environmental profile: transformers

4.2.1 400 kVA transformers

Table 17 Lifetime environmental profile, 400 kVA transformers

Dutch energy model 400 kWA	Climate change (euro / lifetime)	Acidification (euro / lifetime)	Toxics dispersion (euro / lifetime)	**Total (euro / lifetime)**	**Gain rel. to type AA (euro / lifetime)**
type AA	2,584,494.06	246,358.75	547.54	**2,831,400**	**--**
type CC	2,578,230.93	245,913.77	944.03	**2,825,089**	**-6,312**
type C-Amorph	2,558,551.39	244,145.03	1,213.76	**2,803,910**	**-27,490**

EU energy model 400 kWA	Climate change (euro / lifetime)	Acidification (euro / lifetime)	Toxics dispersion (euro / lifetime)	**Total (euro / lifetime)**	**Gain rel. to type AA (euro / lifetime)**
type AA	1,709,348.69	699,831.60	547.54	2,409,728	**--**
type CC	1,705,214.87	698,283.28	944.03	2,404,442	**-5,286**
type C-Amorph	1,692,210.30	693,055.78	1,213.76	2,386,480	**-23,248**

4.2.2 1,600 kVA transformers

Table 18 Lifetime environmental profile, 1,600 kVA transformers

Dutch energy model 1,600 kVA	Climate change (euro / lifetime)	Acidification (euro / lifetime)	Toxics dispersion (euro / lifetime)	**Total (euro / lifetime)**	**Gain rel. to type 1 (euro / lifetime)**
type 1	10,326,313.21	983,997.18	1,362.11	**11,311,673**	**--**
type 2	10,281,481.21	979,955.57	1,955.50	**11,263,392**	**-48,280**
type 3	10,228,875.03	975,466.01	3,304.12	**11,207,645**	**-104,027**

EU energy model 1,600 kVA	Climate change (euro / lifetime)	Acidification (euro / lifetime)	Toxics dispersion (euro / lifetime)	**Total (euro / lifetime)**	**Gain rel. to type 1 (euro / lifetime)**
type 1	6,829,640.63	2,795,863.14	1,362.11	9,626,866	--
type 2	6,800,005.40	2,783,947.03	1,955.50	9,585,908	**-40,958**
type 3	6,765,252.95	2,770,206.23	3,304.12	9,538,763	**-88,103**

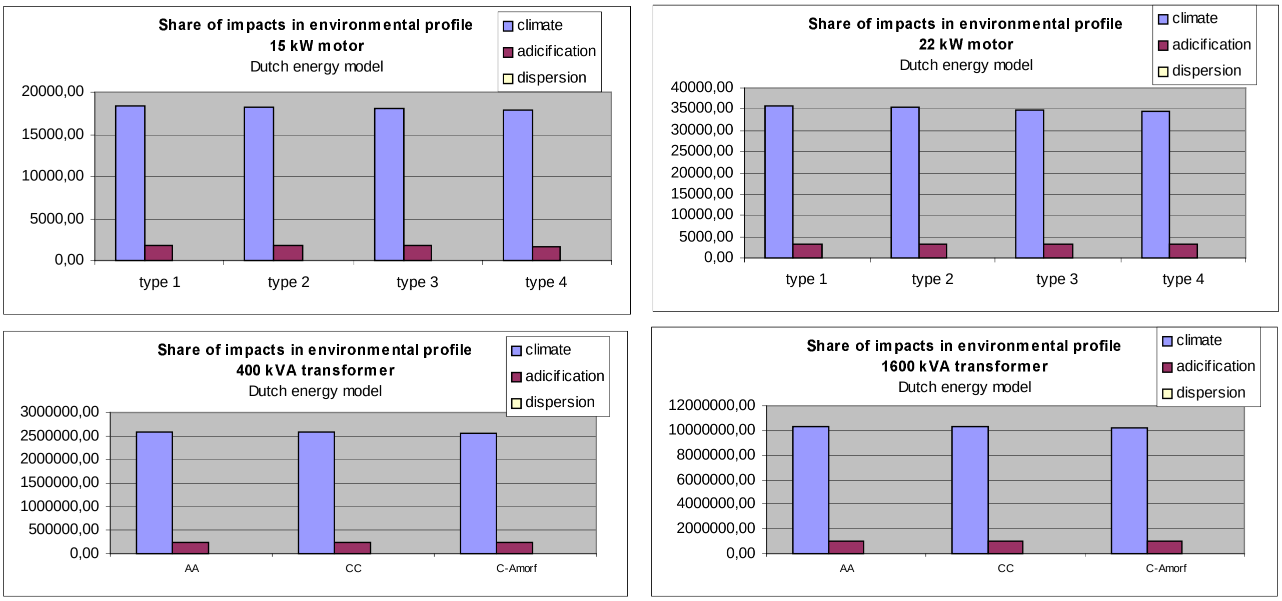
4.3 Analysis of results

The life-cycle environmental impact associated with electric motors and transformers is due overwhelmingly to power consumption during operation, and more specifically to the climate impact of power generation (see Figure 1). For all the types of motor and transformer reviewed in this study the contribution of toxics dispersion to the overall profile is negligible.

On average only 0.2% of the life-cycle environmental burden of motors can be attributed to materials (i.e. metals) use, and 0.05% in the case of transformers, if the Dutch generating park is taken as a reference. If European figures are taken, metals production contributes 0.3% and 0.05%, respectively.

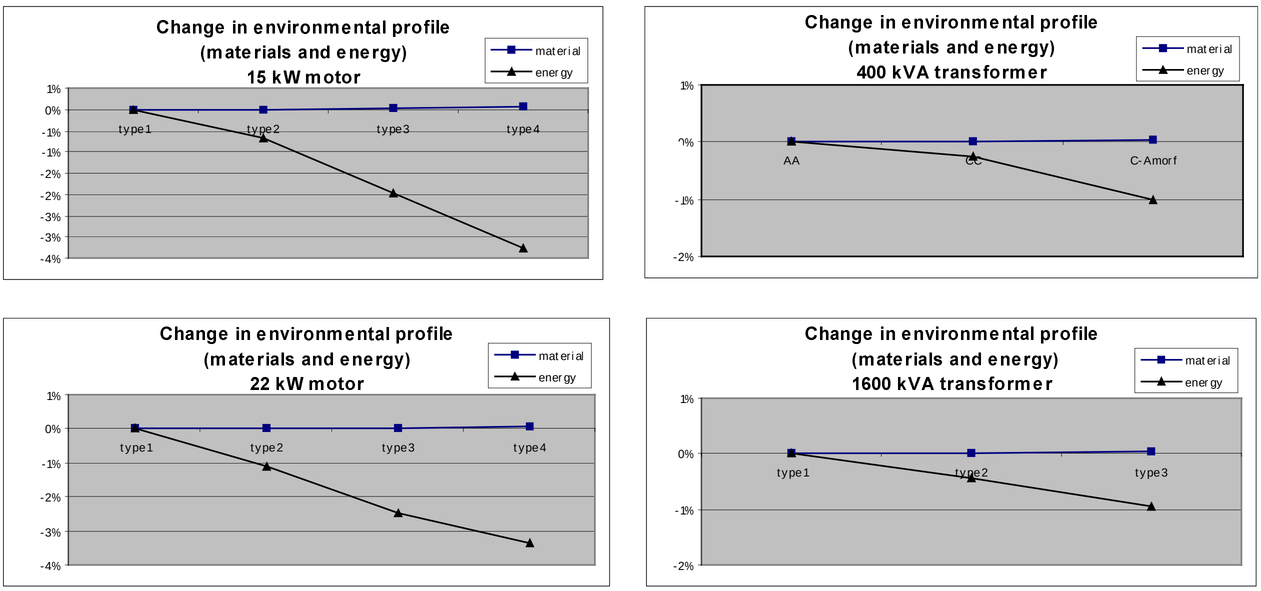
Figure 1 provides a breakdown by environmental theme, for the Dutch model only.

Figure 1 Breakdown of environmental profiles of motors and transformers by environmental theme, in euro per lifetime (Dutch energy model)



As argued above, lifetime environmental performance improves significantly with increasing electrical efficiency. Although any additional materials applied in motor manufacture to improve efficiency bring with them their own environmental burden, the ensuing reduction in operational power requirements gives rise to net environmental gains. This is illustrated graphically in Figure 2.

Figure 2 Net environmental gains from extra materials use and improved electrical efficiency of motors and transformers, relative to reference situation



In the case of electric motors, additional materials use leads to relatively greater efficiency gains. For transformers, the impact of additional materials use on power efficiency is less pronounced.

4.4 Conclusions

For both motors and transformers, the principal life-cycle environmental impact is the greenhouse effect, i.e. climate change, with operational power making the greatest contribution to this theme. This means that any improvement of motor efficiency will substantially benefit the lifetime environmental profile. In this regard, then, wise use of more metal in motor manufacture may provide scope for improving environmental performance.

A word of warning is in order here, however. Using more metal to boost efficiency pays off only very slowly, particularly in the case of transformers. Compared to a type 1 1,600 kVA transformer, for example, the extra metal in a type 3 unit gives rise to an additional 135% lifetime environmental impact, as against 1% less impact due to power consumption.

Literature

[1| Anonymous
Environmental profile report for the European aluminium industry
EAA, Brussels, April 2000.

|2| Habersatter *et al.*
Life Cycle inventories for packagings
BUWAL, Bern, 1998.