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Sustainable Industrial Policy – Building on the Ecodesign Directive – Energy-Using Product Group Analysis/1

Final Report

LOT 2: Distribution and power transformers
Tasks 1 – 7

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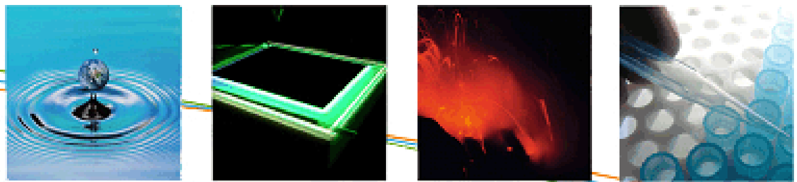

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EXECUTIVE SUMMARY

VITO and BIOIS performed this study for preparing the implementation of the new Ecodesign or Energy Related Products (ERP) Directive (2009/125/EC) related to power and distribution transformers, on behalf of the European Commission (more information available at: http://ec.europa.eu/enterprise/eco_design/index_en.htm). The information provided herein can serve to prepare for subsequent phases, including conducting an impact assessment on policy options, to prepare a paper for the Consultation Forum and finally draft regulation for the Regulatory Committee. Those phases are to be carried out by the European Commission.

The study follows the European Commission's MEEuP methodology and consists of seven Tasks:

1. Definition
2. Economic and market analysis
3. User Behaviour
4. Assessment of Base-Case
5. Technical Analysis BAT and BNAT
6. Improvement Potential
7. Policy and Impact Analysis

Our findings in brief (in Task order) are the following:

Task 1:
Transformers are defined for use in the electrical transmission and distribution systems. These transformers can be segmented according to their application. Distribution Transformers are installed by a Distribution System Operator or end-user and provide most often connection to the Low Voltage (LV) distribution grid (230/400 VAC). These transformers include those used for connecting Distributed Energy Resources (DER) such as wind turbines. Transformers installed by a Transmission System Operator are also referred as 'Power Transformers'. They are used in the Medium Voltage (MV) and/or High Voltage (HV) grid. Another category of smaller industrial transformers are Isolation (Separation) Transformers or Safe Extra Low Voltage (SELV) (control) external power supply transformers. The smaller industrial transformers are constructed according to other standards and are not connected to the medium voltage system, so they can be discriminated easily. According to EN 60076-1 (IEC 60076-1), power transformers are in general terms considered as transformers (including auto-transformers) above 1 kVA single phase and 5 kVA poly phase, hence lower ratings are not considered in this study.

Task 1 also exposes precisely the legislation and standards in use. The most important efficiency parameters of transformers are no-load and load losses, which are responsible for the electricity losses during the use phase. These parameters are covered by different standards depending on the transformer type:

- IEC 60076-1 for power transformers with European equivalent EN 60076-1. In Germany, power transformer designs for oil immersed power transformers from 3150 kVA to 80 MVA for 50Hz and rated voltage up to 123kV have maximum load and no load losses in DIN 42508:2009-08. However this does not cover the full range of European products.
- For oil filled distribution transformers, the European standard (EN 50464-1) includes efficiency classes or 'labels' for load losses (Dk, Ck, Bk, Ak) and no-load losses (Eo, Do, Co, Bo, Ao), and minimum performance levels.
- For dry transformers there is a harmonized document (HD 538) with maximum no-load and load losses. HD 538 will be superseded by EN 50541-1 in 2011.

- EN-61558 series deal with smaller transformers but mainly from a safety perspective.

This task also identifies some other relevant environmental parameters such as noise (covered by IEC 600769-10), electromagnetic fields (EN 50413:2009) and hazardous substances (e.g. PCB ban, under national legislation).

No missing test standards or measurement procedures on energy use and other environmental parameters are identified for power and distribution transformers. For smaller industrial transformers however a gap is highlighted: there is no method to measure the load and no-load losses. However, they use in practice a similar method as distribution transformers (EN 60076-x series).

Several non European countries are also elaborating or have minimum energy performance standards for power and distribution transformers (e.g. Australia and New Zealand, USA, Canada). However, comparisons of these international efficiency classes are not always obvious because of differences in electricity distribution systems. These differences are mainly: voltages, frequencies (50/60 Hz), definitions for apparent power of the transformer (input power versus output power) and load levels at which the efficiency of the transformer is measured (e.g. 50% load, 100% load). For power and distribution transformers, no harmonizing EU Directives apply. For small transformers the Low Voltage Equipment Directive (2006/95/EC) is applicable.

Task 2:
For the total figure of industry and power transformers there should be no doubt that the eligibility criterion (Art. 15, par. 2, sub a, of the Ecodesign Directive) is met as annual sales, in the EU market, are above 200 000 units. Distribution transformers represent the largest share of both the stock and sales. More details about the market size are given in the table below and typical losses are included in the Task report. T&D transformers are mainly produced by large enterprises while smaller industrial transformers often by SMEs (around 50 active in production). Further, transformer prices strongly depend on commodity prices.

Transformer type	Rated Power	Stock			Replacement sales	Total sales		
		1990	2005	2020		1990	2005	2020
	in kVA	*10^3 units*	*10^3 units*	*10^3 units*	*% p.a.*	*units p.a.*	*units p.a.*	*units p.a.*
Smaller Industrial Transformers	16	750	750	750	10	75 000	75 000	75 000
Distribution transformer	250	2 714	3 600	4 459	2.5	119 438	140 400	173 891
DER transformers	2 000	0.25	20	89	4.0	94	2 900	12 967
Industry oil transformer	630	603	800	991	4.0	35 590	43 200	53 505
Industry dry transformer	800	128	170	211	3.3	6 708	8 047	9 966
Power transformer	100 000	49	64.35	80	3.3	2 539	3 046	3 772
Phase	100 000	0.49	0.65	0.81	3.3	26	31	38

The main European industry players for the distribution and power transformers are big international groups (ABB, Siemens, Areva, Schneider Electric), and some large/medium size companies (Cotradis, Efacec, Pauwels, SGB/Smit and Transfix). Transformer manufacturers from outside the EU include GE, Hitachi (Japan) and Vijai (India). T&D Europe is the representative of the European Transformer Manufacturers, regrouping several national associations.

Task 3:
The transformer load profiles have a significant influence on the real life efficiency of the transformer. The characteristic parameters are the Load Factor (α), the Load Form

Factor (Kf) and the availability factor that are defined for different user profiles in this task.

The average technical life of a power or distribution transformer is 25 years or more. The end-user behaviour has a significant impact on the transformer lifetime (e.g. regularly overloading of the transformer). Besides, about 99% (in weight) of the transformers are recycled at the end-of-life phase. This high recycling rate can be explained by the high residual value of the transformer scrap materials.

Task 4:
Based on the European market analysis, seven base-cases are defined:
- BC 1: Distribution transformers (400 kVA)
- BC 2: Industry transformers: oil-immersed (1 MVA)
- BC 3: Industry transformers: dry-type (1.25 MVA)
- BC 4: Power transformers (100 MVA)
- BC 5: DER transformers: oil-immersed (2 MVA)
- BC 6: DER transformers: dry-type (2 MVA)
- BC 7: Smaller industrial separation/isolation transformers (16 kVA)

The environmental impact assessment carried out with the EcoReport tool for each base-case shows that the use phase is by far the most impacting stage of the life cycle in terms of energy consumption, water consumption, greenhouse gases emissions and acidification. The production phase has a significant contribution to the following impacts: generation of non-hazardous waste, Volatile Organic Compounds, Persistent Organic Pollutants, Polycyclic Aromatic Hydrocarbons emissions and eutrophication. Finally, the end-of-life phase is significant for the generation of hazardous waste, the particulate matter emissions and the eutrophication, either due to mineral oil or resin. In particular, the impacts of mineral oil, whose impacts were added in the EcoReport tool, are visible but are also expected to be overestimated in this analysis. Indeed, the end-of-life modelling used the same environmental data as for plastics incineration (environmental impacts and credits) while burning mineral oil with energy recovery is expected to be more efficient than burning plastics with energy recovery. Therefore, the analysis of the improvement potential in Tasks 5-6 focuses on technologies that reduce the electricity losses during the use phase, and also on alternative material (especially oil) reducing environmental impacts.

Despite a small amount of power transformers in stock, these transformers are responsible for about half of the overall impacts of the whole market of power and distribution transformers in EU (see table below). DER transformers still represent a very small share of the overall environmental impacts but it is expected to grow in the near future because of the rising stock of this type of transformer.

Environmental Impact	***BC1***	***BC2***	***BC3***	***BC4***	***BC5***	***BC6***	***BC7***
Total Energy *[PJ]*	199	151	47.3	591	2.6	10.6	4.6
of which electricity *[TWh]*	17.9	13.8	4.36	55.0	0.24	0.96	0.38
Waste, hazardous/ incinerated *[kton]*	41.9	24.7	2.38	61.7	0.40	0.52	0.09
Emissions to air							
Greenhouse Gases *[Mt CO_2 eq.]*	8.8	6.7	2.1	25.9	0.12	0.48	0.21
Volatile Organic Compounds *[kt]*	0.14	0.09	0.02	0.31	0.002	0.005	0.004
Heavy Metals *[ton Ni eq.]*	5.8	4.1	0.95	13.1	0.07	0.22	0.25
Particulate Matter *[kt]*	6.6	3.9	0.63	9.3	0.06	0.20	0.39
Emissions to water							
Eutrophication *[kt PO_4]*	0.049	0.026	0.015	0.06	0.00	0.003	0.001

In general, the share of electricity in the Life Cycle Cost Analysis is significant: from 62% for distribution transformer up to 86% for DER dry-type transformers. Only separation and isolation transformers have a bigger share related for the product price (77%) because of their lower availability factor and their shorter lifetime. Of the total consumer expenditure in 2005, electricity represents 72% of the global amount of money, estimated at 7 453 million euros. Half of this annual expenditure is due to power transformers, which are much more expensive than the other types of transformers (see table below).

Item	BC1	BC2	BC3	BC4	BC5	BC6	BC7	*TOTAL*
EU-27 sales *[units]*	140 400	43 200	8 047	1 802	420	1 680	75 000	270 549
Share of the EU-27 sales	51.9%	16.0%	3.0%	0.7%	0.2%	0.6%	27.7%	100%
Product Price *[mln €]*	860	472	131	1 297	8	47	101	2 916
Electricity *[mln €]*	1 385	1 068	338	4 277	71	284	30	7 453
Total *[mln €]*	2 244	1 540	470	5 574	79	331	131	10 369

Task 5:

This task examines the improvement options of transformers considered as best available technologies, in an attempt to improve upon the base-cases. Transformers can be improved by using similar technology based on silicon steel transformers with the following options:

- The use of copper compared to aluminium conductors;
- The use of a circular limb core cross-section;

Also, other potential improvements include:

- The use of High permeability Grain Oriented Electrical Steel (HGO) with lower losses (Cold rolled Grain-Oriented steel, High permeability steel, Domain Refined high permeability steel);
- The use of amorphous steel (significant lower core losses) (not possible to larger power transformers);
- The use of transformers with silicon liquid, synthetic esters or biodegradable natural esters instead of dry cast resign transformers or mineral oil;
- Increasing the cross section of the conductor and cross section of the core;
- Core construction techniques (e.g. mitred lapped joints);
- The transformer design variability combining above improvements;
- Improved coatings between the laminations of conventional silicon steel;
- Reducing the transformer noise.

All improvement options increase the product price. Several improvement options increase the product volume and mass.

The improvements options considered as Best Not yet Available Technologies concern:

- Further improvements of Grain oriented magnetic steels, amorphous microcrystalline material as core materials;
- The use of superconducting technology;
- The use of smart grid technology to switch off a by-pass transformers off peak load (system level);

Task 6:

As accomplished in Task 4, the EcoReport tool is used in order to assess environmental and economic impacts of the base-case with improvement options. With some exceptions, the improvement options prove to be economically superior and more energy efficient. However, these improvement options are inferior regarding certain environmental impacts related to increased material use, such as waste, particulate matter, and eutrophication.

A sensitivity analysis is conducted to examine the effect of assumptions made throughout the study on final results. It is concluded that while the results do change in absolute numbers, generally the results remain the same relative to the base-case. Therefore, it confirms that the results obtained are robust and not significantly dependent upon input assumptions. The factors investigated include load factors, load form factors (for DER transformers), lifetimes, electricity prices, transformer prices, discount rate and installed stock.

Task 7:

Several policy options are proposed with a strong focus on the decrease of transformer load and no-load losses compared to Business as Usual (BAU). The chapter also includes recommendations on product definitions and the scope of the proposed measures. The table below summarises the Minimum Energy Performance Standard (MEPS) proposals for the distribution and power transformers.

<table>
<tr><th>Product category</th><th>Base-cases included</th><th>MEPS Tier 1 (2013)</th><th>MEPS Tier 2 (2018)</th><th>Comment</th></tr>
<tr><td rowspan="2">Oil-immersed distribution transformers

Subcategory: pole mounted transformers</td><td>BC 1, BC 2, BC 5</td><td>For ≤630 kVA: A0Ck
For >630 kVA: A0Ak</td><td rowspan="2">Harmonisation to avoid having a subcategory</td><td>MEPS in line with Least Life Cycle Cost (LLCC) options (amorphous options excluded)</td></tr>
<tr><td>none</td><td>low loss core material (≤0,95 W per kg at 1,7 T at 50 Hz) if not possible to meet generic MEPS</td><td>-</td></tr>
<tr><td>Dry-type distribution Transformers</td><td>BC 3, BC 6</td><td>A0Ak</td><td>-</td><td>MEPS in line with LLCC options (slightly more ambitious for BC 3 to have a consistent regulation between oil-immersed and dry-type transformers)</td></tr>
<tr><td>Large Power Transformers</td><td>BC 4</td><td>See Table 7-3</td><td>-</td><td>MEPS more ambitious than LLCC (see text for justification) but less ambitious than the BAT</td></tr>
<tr><td>Smaller Power Transformers</td><td>BC 7</td><td>-</td><td>See Table 7-4</td><td>MEPS in line with LLCC option (Business as Usual(BAU)) for Tier 1, more ambitious target kept for Tier 2</td></tr>
</table>

Because of weight limitations, it might be that some pole mounted transformers can technically not satisfy the proposed maximum loss requirements of the category 'oil-immersed distribution transformers'. For these transformers, an alternative requirement on core loss alone (W/kg) is proposed. These transformers could also benefit from strict installation requirements in Member States. There are also generic ecodesign requirements proposals on the supply of product information. The reasons why the authors believe that strictly implementing identified LLCC (A0+Ck, ≤630 kVA) for oil-immersed distribution transformers cannot be done in the medium term (Tiers 1 and 2) are related to the uncertainty on the availability of amorphous material, transformer production in the EU, copper price, maintaining transformer price competition and some small functional differences of amorphous transformers (compactness, etc.). However on the long term (Tier 3) such a target can be considered.

There is a need for updated harmonized standards to measure smaller transformer and large power transformers losses and proposals to fill these gaps are formulated. For several standards, updates are recommended, especially to add extra no load losses categories in standards EN50464-1 and prEN 50541-1 to cover BAT developments.

Policy recommendations such as benchmarking, financial incentives or Green Public Procurement (GPP) are made to promote efficient power and distribution transformers. Several TSO/DSOs currently use a Total Cost of Ownership (TCO) that takes into account load and no-load losses. The TCO is also a suitable tool to drive the market towards more efficient transformers. It should however not replace exclusively the MEPS but should only be used as a complementary tool to go beyond the MEPS in terms of energy efficiency if it is economically justified. Recommendations are made on the current TCO approach to increase consistency with an energy efficiency policy and the EU 20/20/20 targets.

This chapter also includes proposals for policy actions related to Best Not yet Available Technology (BNAT). Amongst others, more research is needed on fire behaviour of liquid filled transformers with silicon liquid or biodegradable natural esters and the creation of a standard could be considered.

The scenario analysis shows that significant energy savings are possible from a LLCC or BAT scenario over BAU, achieving up to 16 % and 28% electric savings in 2025 from 102 TWh (BAU, annually in 2025), respectively. A MEPS scenario is also elaborated and would reduce by 17.2% the electricity losses in 2025, saving 17.8 TWh. In addition, the LLCC scenario is economically advantageous and saves 1.5% of expenditures in 2025, while providing overall economic savings since 2011 starting in 2032. The MEPS scenario is expected to provide overall economic savings in 2048 (assuming that the electricity tariff will not increase).

There is also a section related to impact of policy measures. Most important is the lack (anno 2010) of amorphous material and transformer production capacity within Europe.

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LIST OF ACRONYMS

AC	Alternating Current
AF	(Transformer) Availability Factor
AISI	American Iron and Steel Institute
Al	Aluminium
AM	Amorphous Metal
AMDT	Amorphous Metal Distribution Transformer
AMT	Amorphous Metal Transformer
AP	Acidification Potential
avg	average
BAT	Best Available Technology
BAU	Business As Usual
BEE	Bureau of Energy Efficiency
BNAT	Best Not yet Available Technology
BOM	Bill of Materials
CENELEC	European Committee for Electro technical Standardization
CGO	Cold rolled Grain-Oriented Steel
COTREL	European Sector Committee for Transformer Manufacturers
CSA	conductor cross-sectional area
Cu	Copper
Cu-ETP	Electrolytic Tough Pitch Copper
DAO	Distribution Asset Owner
DER	Distributed Energy Resources
DHP	Dry High Power
DLP	Dry Low Power
DOE	US Department of Energy
DSO	Distribution System Operators
ELF	Extremely Low frequency
EMC	Electro Magnetic Compatibility
EMF	Electromagnetic fields
EN	European Norm
EP	Eutrophication Potential
EPRI	Electric Power Research Institute
ERGEG	European Regulator group for Electricity and Gas
ETSI	European Telecommunications Standards Institute
EU	European Union
EuP	Energy using Products
ERP	Energy Related Products
EWEA	European Wind Energy Association
GO	Grain Oriented
GSU	Generator Step Up (transformer)
GWP	Global Warming Potential
HD	Harmonization Document
HiB	High-permeability steel
HiB-DR	Domain Refined High-permeability steel
HGO	High-permeability steel
HGO-DR	Domain Refined High-permeability steel
HM	Heavy Metals
HTS	high-temperature superconducting
HV	High Voltage
HVDC	High Voltage DC
Hz	Hertz
IEC	The International Electro technical Commission
IEE	Intelligent Energy Europe

IEEA	Intelligent Energy Executive Agency
IEEE	Institute of Electrical and Electronics Engineers
IP	Isolation Protection
JRC	Joint Research Centre
k	Kilo (10^3)
Kf	Load form factor
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LHP	Liquid High Power
LLP	Liquid Low Power
LMHP	Liquid Medium High Power
LMLP	Liquid Medium Low Power
LV	Low Voltage
LVD	Low Voltage Directive
MEEuP	Methodology for the Eco-design of Energy using Products
MEPS	Minimum Energy Performance Standard
MV	Medium Voltage
NEEAP	National Energy Efficiency Action Plan
NEMA	National Electrical Manufactures Association
NIEHS	National Institute of Environmental Health Sciences
OFAF	Oil Forced Air Forced
OFAN	Oil Forced Air Natural
OFWF	Oil Forced Water Forces
ONAF	Oil Natural Air Forced
ONAN	Oil Natural Air Natural
PAH	Polycyclic Aromatic Hydrocarbons
PAHs	Polycyclic Aromatic Hydrocarbons
Paux	Auxiliary losses
PCB	Polychlorinated Biphenyl
PF	Power factor
Pk	Load losses
PM	Particulate Matter
Po	No load losses
POP	Persistent Organic Pollutants
PRODCOM	PRODuction COMmunautaire
PWB	Printed Wiring Board
RECS	Renewable Energy Certificate System
REMODECE	Residential Monitoring to Decrease Energy Use and Carbon Emissions in Europe
RES	Renewable Energy Sources
rms	root mean square
RoHS	Restriction of the use of certain Hazardous Substances in electrical and electronic equipment
S	(transformer) apparent power
SEEDT	Strategy for development and diffusion of Energy Efficient Distribution Transformers
SEEDT	Selecting Energy Efficient Distribution Transformers'
SELV	Safe Extra Low Voltage
SF	Simultaneity Factor
Si	Silicon
SME	small medium sized enterprise
TBC	To Be Confirmed (should appear in the draft version only)
TBD	To Be Defined (should appear in draft versions only)
TAO	Transmission Asset Owners
TC	Technical Committee
TCO	Total Cost of Ownership

TOC	Total Operational Cost
TR	Technical Report
TSO	Transmission System Operators
TWh	TeraWatt hours
ENTSOE	Union for the Coordination of the Transmission of Electricity
UF	Utilisation Factor
UPS	Uninterruptible Power Supply
USA	United States of America
V	Volt
VA	Volt-Ampere
VITO	Flemish Institute for Technological Research
VOC	Volatile Organic Compounds
WEEE	Waste Electrical and Electronic Equipment
Z	Short-circuit impedance
α	Load Factor

CHAPTER 1 DEFINITION

Scope: The objective of this task is to discuss definition and scope (from a functional, technical, economic and environmental point of view) for the eco-design preparatory study for the ENTR Lot 2 and to define the product category and the system boundaries of the 'playing field'. It consists of the categorization of distribution and power transformers according to Prodcom categories (used in Eurostat) and to other schemes (e.g. EN standards), description of relevant definitions and of the overlaps with the Prodcom classification categories, scope definition, and identification of key parameters for the selection of relevant products to perform detailed analysis and assessment during the next steps of the study. Discussion of products definition and scope issues also includes an analysis of product-system interactions in relation to the products' environmental impacts and potential improvements.
Further, harmonized test and performance standards and additional sector-specific procedures for product-testing will be identified and discussed, covering the test protocols for:

- Primary and secondary functional performance parameters (Functional Unit)
- Resource use (energy, etc.) during product-life
- Safety (electricity, EMC, stability of the product, etc.)
- Other product specific test procedures.

Finally, this task identifies existing legislations, voluntary agreements, and labelling initiatives at the EU level, in the Member States, and in the countries outside the EU.
This task also classifies Lot 2 equipment into appropriate product groups while providing a first screening of the volume of sales and stock, environmental impacts and improvement potential for these products.

Summary of Task 1:
Transformers are defined for use in the electrical transmission and distribution systems. These transformers can be segmented according to their application. They can be installed either by Transmission System Operators (TSO), or Distribution System Operators (DSO), or alternatively by the industrial or the tertiary sector end user themselves. Distribution Transformers are installed by a DSO or end user and provide most often connection to the Low Voltage (LV) distribution grid (230/400 VAC). These transformers include those used for connecting Distributed Energy Resources (DER) such as wind turbines. Transformers installed by a TSO are also referred as 'Power Transformers'. They are used in the Medium Voltage (MV) and/or High Voltage (HV) grid. Another category of smaller industrial transformers are Isolation (Separation) Transformers or Safe Extra Low Voltage (SELV) (control) external power supply transformers (e.g. 24 VAC). The smaller industrial transformers are constructed according to other standards and not connected to the medium voltage system, so they can be discriminated easily.
According to EN 60076-1 (IEC 60076-1), power transformers are in general terms considered as transformers (including auto-transformers) above 1 kVA single phase and 5 kVA poly phase, hence lower ratings are not considered in this study.
Apart from their application, transformers can be further segmented according to their technology or functionality, see below:

Study scope	Major subcategory name	Type of Service and Sector	Main Type of Technology used or Functionality: Oil cooled	Dry-type	Gas-filled	MV/LV	HV and/or MV	Phase change	LV/LV	Copper winding	Aluminium winding	Amorphous steel core	S Min (kVA)	S Max (kVA)	S Avg (kVA)
y	**MV/LV Distribution transformer**	Distribution by DSO	99.99%	0.01%		100%				90%	10%	<100	50	2500	250
n	**line voltage restorers**	Distribution by DSO		100%					yes	100%			10	50	25
y	**DER LV/MV transformers**	Connecting DER by producer	20%	80%		100%				80%	20%	0%	50	2500	2000
y	**Industry MV/LV oil transformer**	Distribution by non DSO (industry, ..)	50%			100%				85%	15%		50	2500	630
y	**Industry MV/LV dry transformer**	Distribution by non DSO (industry, ..)		50%		100%				15%	85%		50	4000	800
y	**Power transfomer**	Power by TSO (DSO)	100%		0%		99%			100%			5000	>	1E+05
y	**Phase shifter**	Power by TSO (DSO)	100%		0%			1%		100%			5000	>	1E+05
y	**Seperation/isolation transformer**	Distribution by non DSO (industry, ..)		100%						100%			1	63	16
y/n	**Control transformer**	Distribution by non DSO (industry, ..)		100%					yes	100%			0.04	2.5	1.6
n	**Safety transformers**	Specific ext. applications industry/domestic		100%					yes	100%			0.04	0.25	0.06
n	**speciality/consumer transformers**	Specific int. application industry/domestic	NA	NA		NA	NA		yes	NA	NA	NA	NA	NA	NA
n	**magnetic halogen transformers**	Lighting all sectors		100%					yes	100%			0.04	0.63	0.06

Task 1 also exposes precisely the legislation and standards in use. The most important efficiency parameters of transformers are no-load and load losses, which are responsible for the electricity losses during the use phase. These parameters are covered by different standards depending on the transformer type:

- The IEC 60076-1 is the general generic standard for power transformers with European equivalent EN 60076-1.
- For oil filled distribution transformers, the European standard (EN 50464-1) includes efficiency classes or 'labels' for load losses (Dk, Ck, Bk, Ak) and no-load losses (Eo, Do, Co, Bo, A0).
- For dry transformers there is a harmonized document (HD 538) with maximum no-load and load losses. HD 538 will be superseded by EN 50541-1 in 2011.
- EN-61558 series deal with smaller transformers but mainly from a safety perspective.
- For distribution and industrial transformers there are minimum performance levels for load and no load losses defined in standards EN50464-1, HD 538.1 or FprEN50541-1. A final recommendation on raising the existing minimum energy performance level is a topic of Task 7 on policy recommendations after the full analysis in the subsequent tasks.
- Also, the highest performance level (Ak, A0) defined in standards EN50464-1, HD 538.1 or FprEN50541-1 does not mean that significant lower losses cannot be achieved with actual technology. This is also evaluated in subsequent tasks.
- In Germany, power transformer designs for oil immersed power transformers from 3150 kVA to 80 MVA for 50Hz and rated voltage up to 123kV have maximum load and no load losses in DIN 42508:2009-08.

This task also identifies some other relevant ecodesign or environmental parameters for power and distribution transformers which are: noise (covered by IEC 600769-10), electromagnetic fields (EN 50413:2009) and hazardous substances (e.g. PCB ban, under national legislation).

No missing test standards or measurement procedures on energy use and other environmental parameters have been identified for power and distribution transformers. For smaller industrial transformers however a gap has been identified, there is no standard formal to measure the load and no load losses. However they use in practice a similar method as distribution transformers (EN 60076-x series). This gap should be closed as soon as possible. There are no Minimum Energy Performance Standard (MEPS) reported for these small industrial transformers. Therefore MEPS are considered in Task 7 on policy recommendations, based onthe full analysis in the subsequent tasks.

MEPS for power transformers are defined in DIN 42508:2009-08, however this does not cover the full range of European products. Currently most European TSOs have their own public tender specifications that take load and no-load losses into account when assessing the Total Cost of Ownership (TCO).

Several non European countries are also elaborating or have minimum performance efficiency standards for power and distribution transformers (Australia and New Zealand, USA, Canada, etc.). However, comparisons of these international efficiency classes are not always obvious because of differences in electricity distribution systems (voltages, frequencies…), in definitions for apparent power of the transformer (input power versus output power) and in load levels at which the efficiency of the transformer is measured (50% load, 100% load…).

For power and distribution transformers no harmonizing EU Directives apply. For small transformers the Low Voltage Equipment Directive (2006/95/EC) is applicable.

1.1 General context and scope

The overall context of this preparatory study is the electricity transmission and distribution (T&D) system (see Figure 1-1 and Figure 1-2) and industrial systems. In the alternating current (AC) electrical supply system that is used in all countries for supply to consumers, the transformer is an indispensable component.

The generated electricity goes through various transformations; e.g. stepping up the voltage in order to transmit over large distances and various levels of stepping down the voltage to its final end-user (domestic, commercial, or industrial use). Transformers convert electrical energy from one voltage level to another. They are an essential part of the electricity network. After generation in power stations, electrical energy needs to be transported to the areas where it is consumed. This transport is more efficient at higher voltage, which is why power generated at 10 - 30 kV is converted by transformers into typical voltages of 220 kV up to 400 kV, or even higher. Since the majority of electrical installations operate at lower voltages, the high voltage needs to be converted back close to the point of use. The main reason to step down voltage is to increase the safety for the end user and insulation material. The first step down is transformation to 33 - 150 kV. It is often the level at which power is supplied to major industrial customers. Distribution companies then transform power further down to the consumer mains voltage.

In this way, electrical energy passes through an average of four transformation stages before being consumed. A large number of transformers of different classes and sizes are needed in the transmission and distribution network, with a wide range of operating voltages. Large transformers for high voltages are called power transformers. The last transformation step into the consumer mains voltage (in Europe 400/230 V) is done by the distribution transformer.

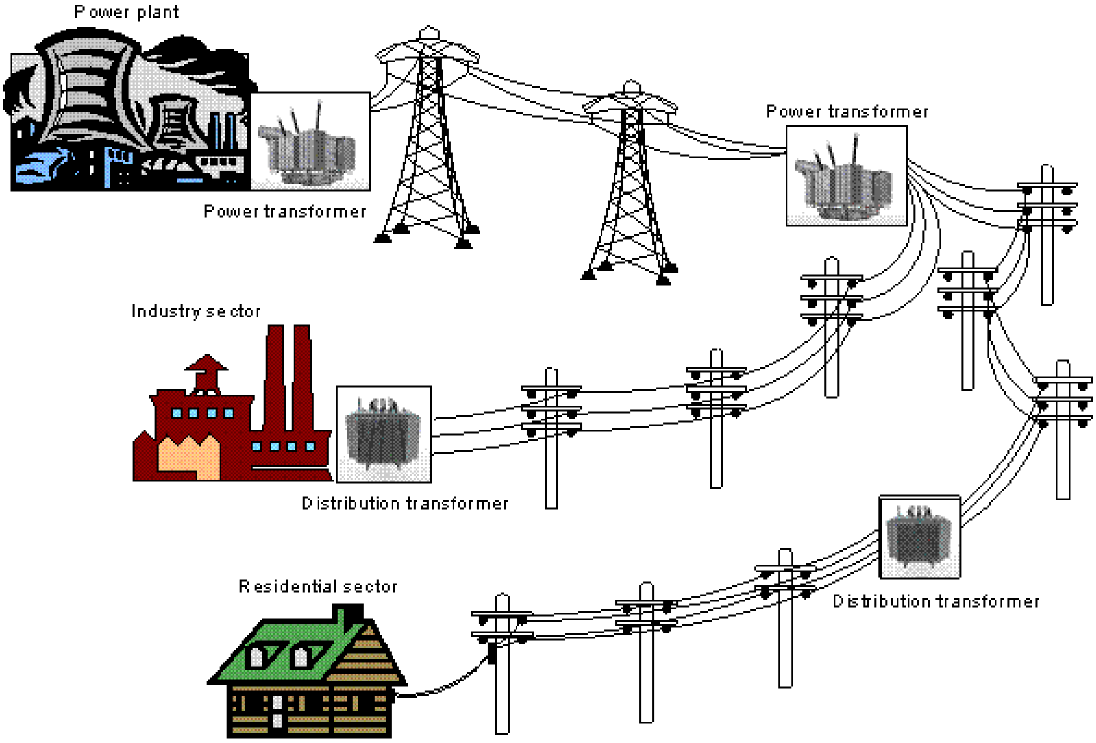

Figure 1-1: Overall context is the electricity and transmission distribution (T&D) system

Transformers are installed at the side of generation and in transmission and distribution (T&D).
The total electrical energy use per annum of the EU-25 is about 2 771.6 Terra Watt hours (2005) [TWh] (1 TWh = 10^9 kWh). It is further estimated (Leonardo Energy Transformers, February 2005[1], Eurelectric, 2006[2]) that the losses in all EU's electrical distribution systems are about 200 TWh or 7.2% of the total electrical energy consumed. About 30-35% of these losses are generated in the transformers in the distribution systems, meaning between 60 TWh and 70 TWh, or between 2.4% and 2.8% of total electrical energy consumed (Leonardo Energy Transformers, February 2005[1]).
Transformers can be installed by Transmission System Operators (TSO), Distribution System Operators (DSO) or alternatively by the industrial or the tertiary sector end user themselves. DSOs are also called Utilities and they often distribute other commodities such as gas and water. The transmission system is typically operated at higher voltages while the distribution system at lower voltages as schematically represented in Figure 1-2. Industry also frequently uses smaller transformers for isolated electrical grids or 24 VAC power supply for automation equipment.

[1] Leonardo Energy Transformers, 'Potential for global energy savings from high efficiency distribution transformers', February 2005
[2] Eurelectric, Statistics and prospects for the European lectricity sector, December 2006

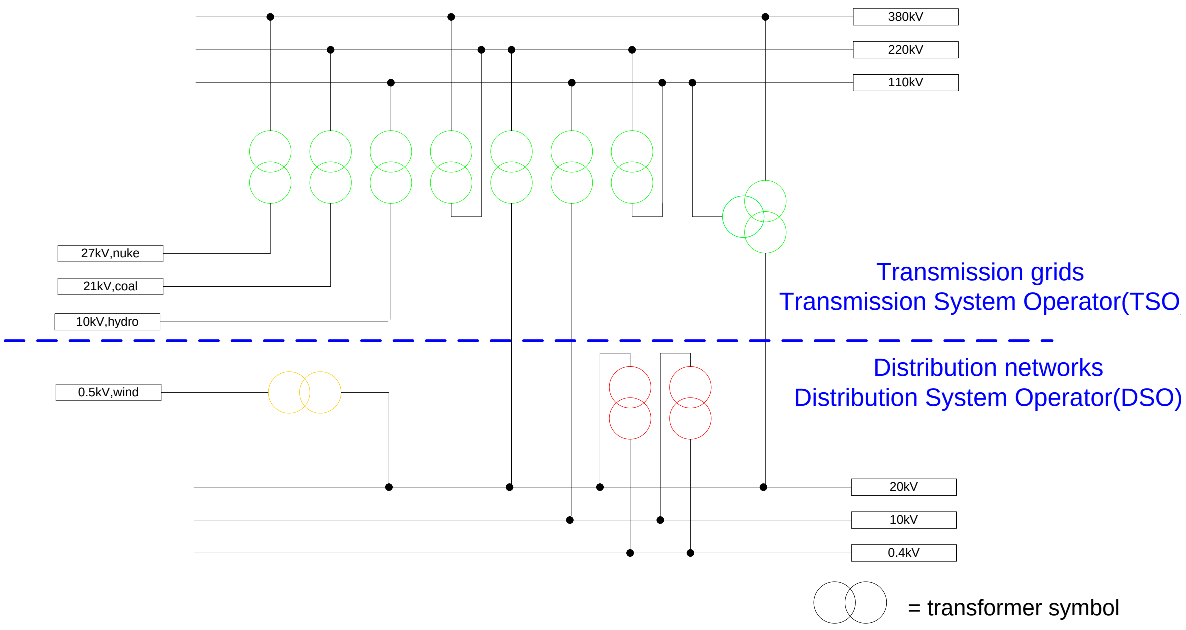

Figure 1-2: Schematic diagram of the electrical Transmission and Distribution (T&D) system (voltage level typical for Germany but can differ per country)

Modern distribution transformers are typically about 98-99% efficient at half load (SEEDT, 2008[3]). This might suggest a low improvement potential to improve their environmental performance. However, due to the very large number of transformers in use in the distribution systems, the total impact of small improvements could provide a significant contribution to reduce environmental impacts, such as global warming and climate change.
Please note that industry sometimes also installs additional so-called smaller industrial power transformers in the distribution line for safety, lower voltages or special applications.

1.2 Basic concept of a transformer

A transformer is defined as a static piece of apparatus with two or more windings which, by electromagnetic induction, transforms a system of alternating voltage and current into another system of voltage and current usually of different values and at the same frequency for the purpose of transmitting electrical power (IEC 60050).

The construction of a transformer (Figure 1-3) comprises two active components: the ferromagnetic core and the windings. Within the transformer industry, the core and windings together are normally referred to as the “active part”. The passive part of a transformer is the cooling system, e.g. consisting of a tank and the cooling liquid. A transformer uses the core's magnetic properties and current in the primary winding (connected to the source of electricity) to induce a current in the secondary winding (connected to the output or load). Alternating current in the primary winding induces a magnetic flux in the core, which in turn induces a voltage in the secondary winding. A voltage step-down results from the exchange of voltage for current, and its magnitude is determined by the ratio of turns in the primary and secondary windings. A

[3] Strategies for development and diffusion of Energy Efficient Distribution Transformers (SEEDT), Analysis of existing situation of energy efficient transformers – technical and non-technical solutions, 2008)

transformer with 50 primary turns and five secondary turns would step the voltage down by a factor of 10, for example from 1000 volts to 100 volts. The transformer in Figure 1-3 is an example of a typical distribution transformer. In the next sections a broader range of transformers will be covered. Transformer 'bushing ' is an insulating liner in an opening through which conductors pass that allow connection to the electrical grid.

Figure 1-3: Cutaway view of a distribution transformer

1.3 Identification of the main ecodesign parameters for energy losses and other environmental impacts

This study will focus on the whole environmental impact assessment of transformers based on ecodesign parameters.
ANNEX I of the Ecodesign Directive 2009/125/EC describes these relevant ecodesign parameters.
For each phase of the life cycle of transformers, the following environmental aspects are to be assessed where relevant:

(a) predicted consumption of materials, of energy and of other resources such as fresh water;
(b) anticipated emissions to air, water or soil;
(c) anticipated pollution through physical effects such as noise, vibration, radiation, electromagnetic fields;
(d) expected generation of waste material;
(e) possibilities for reuse, recycling and recovery of materials and/or of energy.

Note: It is quite common to have Minimum Energy Performance Standards for these transformers globally, see also section 1.87.
Hence, the most prominent focus when analyzing the environmental impact of Energy Related Products (ERPs) was currently on the use phase and energy use, for transformers being electricity use.

A Life Cycle Assessment (LCA) method will be used based on the MEEuP Methodology report (see project website) which is commonly accepted for these studies.
The MEEuP methodology report summarizes environmental impact into 14 environmental indicators (and 2 auxiliary parameters). These environmental indicators are Energy, Water (process & cooling), Waste (hazardous & non-hazardous), Global

Warming Potential (GWP), Acidification Potential (AP), Volatile Organic Compounds (VOC), Persistent Organic Pollutants (POP), Heavy Metals (to air & to water) carcinogenic Polycyclic Aromatic Hydrocarbons (PAH), Particulate Matter (PM) and the Eutrophication Potential of certain emissions to water (EP).
Other environmental parameters are treated on an ad hoc basis or derived from one or more of the indicators that are quantified.
In line with ANNEX 1 the *ad hoc environmental parameters* identified for transformers are:

1. Noise
Transformers can produce a humming noise in the range of 100 Hz with harmonics up to 2000 Hz. Transformer acoustic noise[4] is a hum characterized by spectral spikes at harmonics of the fundamental frequency of 100 Hz which is twice the line supply frequency. This might cause nuisance or discomfort, e.g. when installed in the basement of an apartment building. Please note that transformer noise measurements are regulated in standards but no limits are set. The limits are imposed by installation requirements and related noise legislation. In Japan noise levels are determined in accordance with the installation environment which is for DSO regulated at <45 dB in rural areas and 50 dB in other areas. It is obvious to link noise requirements to installation rather then a product requirement as such.

2. Electromagnetic fields (EMF)
Transformers produce so called 'Extremely Low frequency' (ELF[5]) fields of 50 Hz. So-called ELF fields are defined frequencies up to 300 Hz. A typical installation requirement is 0,1 mT (e.g. Japan).

3. Use of hazardous materials in transformers
Some transformers contain hazardous materials, they are:

- Some products in operation may still comprise polychlorinated biphenyls or *PCB*s, however it is not allowed anymore in new transformers. This might be very few nowadays as in many countries it is a criminal offence.
- Oil filled distribution transformers mostly contain *Mineral transformer oil* if released into the environment in the case of a fault, pollutes the ground and will possibly jeopardize the ground water. In this case Biodegradable insulating/coolant liquid may be used that is biodegradable and not water pollutant and furthermore has a much higher flash point than the mineral oils traditionally used. Biodegradable oil has a poorer cooling effect and hence causing larger volumes/more materials as well. Synthetic oil is rarely used (e.g.) Midol, only for special use such as water protection areas. Modern installation often comprises binding and controlled drainage to solve these problems at installation level.
- A few power transformers use *Sulphur hexafluoride (SF6) gas* and they are sometimes referred to as a gas-insulated transformer. It could be an environmental issue because it's strong impact on global warming (1 SF6 = 23 600 CO2). This gas is mainly used in electrical switchgear but according to Orgalime they are rarely used (less than 100); hence it is not an issue for this study. SF6 is mainly used in TSO switchgear but this is outside the scope of this study.

[4] Ravish S. Masti et al. (2004) 'On the influence of core laminations upon power transformer noise', PROCEEDINGS OF ISMA2004.
[5] http://www.who.int/peh-emf/about/WhatisEMF/en/

All above aspects will be discussed in details in the next tasks, especially Tasks 3 and 4. The environmental assessment carried out in Task 4 will allow identifying impacts for 13 environmental indicators during the whole life cycle of transformers.

This Life Cycle Assessment approach would ensure that all relevant environmental impacts will be analyzed, and that any tradeoffs, when assessing the improvement options in task 6, will be identified.

Background info on energy losses in transformers:

Transformer efficiency losses consist of:

- *No load losses (Po)*: these losses occur when the secondary circuit is open and the primary one is at its rated voltage (HV). In that case there is only a small primary current and joule effect losses are negligible. No-load losses are composed of:
  - Hysteresis losses, caused by the frictional movement of magnetic domains in the core laminations being magnetized and demagnetized by alternation of the magnetic field. These losses depend on the type of material used to build a core. Hysteresis losses are usually responsible for more than a half of total no-load losses (50-70%).
  - Eddy current losses, caused by varying magnetic fields inducing eddy currents in the laminations and thus generating heat. These losses can be reduced by building the core from thin laminated sheets insulated from each other by a thin varnish layer to reduce eddy currents.
  - There are also marginal stray and dielectric losses which occur in the transformer core. Stray losses, due to stray magnetic fields, cause eddy currents in the conductors or in surrounding metal. Dielectric losses in the insulating materials - particularly in the oil and the solid insulation of high voltage transformers. They account usually for no more than 1% of total no-load losses.
- *Load losses (Pk)*: They are a function of the load factor. Their value at rated load is determined when the secondary circuit is short-circuited and the primary is supplied at rated current (S/LV). These losses are commonly called copper losses or short circuit losses. Load losses are composed of:
  - Ohmic heat loss in the transformer windings sometimes referred to as copper loss or Joule effect losses. The magnitude of these losses increases with the square of the load current and is proportional to the resistance of the winding.
  - Conductor eddy current losses. Eddy currents are caused by the magnetic fields of alternating current. They also occur in the windings, tanks and metal parts. Amongst others, stranded conductors are used to lower the eddy current loss.
- *Auxiliary losses (Paux)*: These losses are caused by using energy to run cooling fans or pumps which help to cool transformers.

Background information on negative health effects of Electric and magnetic fields (EMF) from power lines and transformers (source EPA[6] (2009)):

EMF is commonly associated with power lines. Many people are concerned about potential adverse health effects. Much of the research about power lines and potential health effects is inconclusive. Despite more than two decades of research to determine whether elevated EMF exposure, principally to magnetic fields, is related to an increased risk of childhood leukemia, there is still no definitive answer. The general

[6] http://www.epa.gov/rpdweb01/power-lines.html

scientific consensus is that, thus far, the evidence available is weak and is not sufficient to establish a definitive cause-effect relationship.
In 1998, an expert working group, organized by the National Institute of Health's National Institute of Environmental Health Sciences (NIEHS), assessed the health effects of exposure to extremely low frequency EMF, the type found in homes near power lines. Based on studies about the incidence of childhood leukemia involving a large number of households, NIEHS found that power line magnetic fields are a possible cause of cancer. The working group also concluded that the results of EMF animal, cellular, and mechanistic (process) studies do not confirm or refute the finding of the human studies. The International Agency for Research on Cancer (WHO) reached a similar conclusion.

1.4 Methodology of this study

This study will follow a methodology common to all the ERP (EuP) preparatory studies: Methodology for Eco-design of Energy-using Products (MEEuP). An overview of the 7 task structure of the study is presented in the following Figure 1-4. The results of each task are included in chapters with the same numbering. The methodology used is the same as that approved by the European Commission for all ERP (EuP) preparatory studies. For further details on the methodology, see the MEEuP final report that is available on the project website (www.ecotransformer.org).

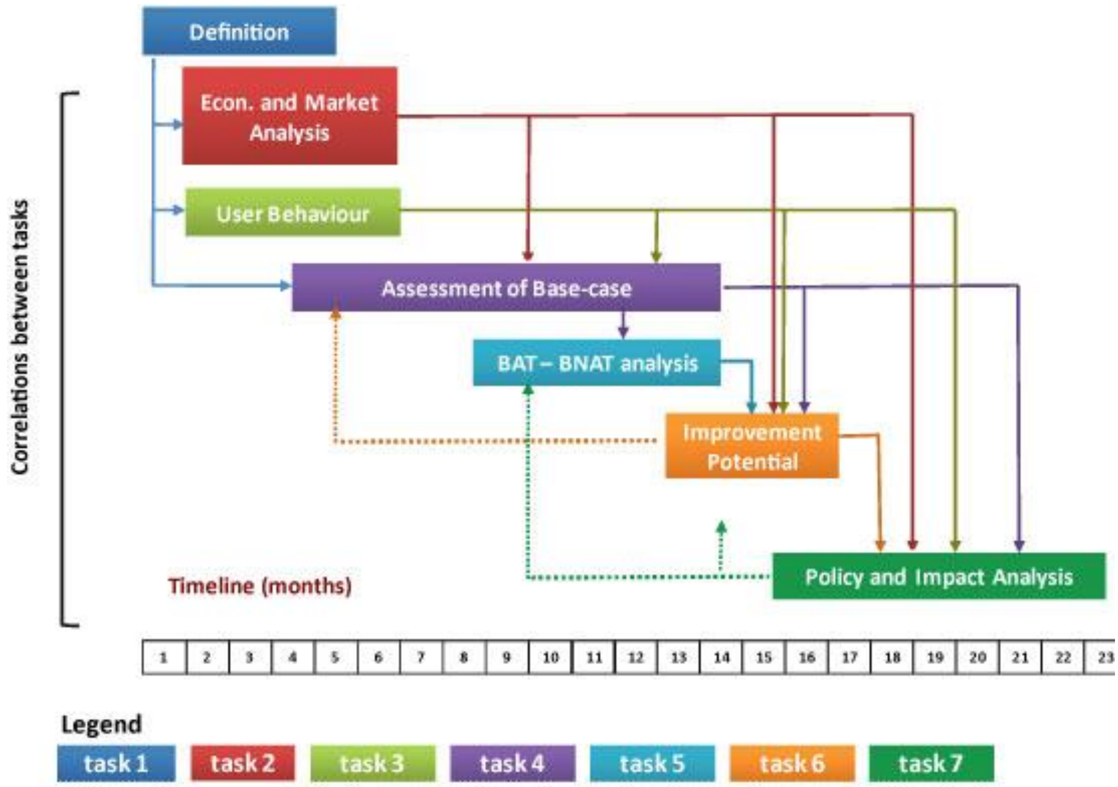

Figure 1-4: MEEuP methodology and planning of this study.

1.5 Product definition

This section defines the categories of products covered by this study and defines the performance parameters.

1.5.1 Key methodological issues related to the product definition

The experience from previous ERP (EuP) preparatory studies indicates that in order to select a proper product scope and complementary definition from the existing options (e.g. definitions and scopes derived from market statistics, technical standards, and labelling schemes) it is necessary to reflect or match the boundaries of this product with the task requirements of the whole study. This means that the product definition needs to fit:

- Test standards reflecting environmental issues including power consumption measurement procedures (task 1)
- Other performance related standards (task 1)
- Product performance parameters and respective functional unit (task 1)
- Product and technology trends (task 2 and 6)
- Available market data and respective typical market segmentation (task 2 and 4)
- Use environments and respective typical use patterns (task 3 and 4)
- Products design characteristics and respective technical parameters (task 4)
- Environmental impact magnitudes and expected improvements (task 5)

Against this background, the first subtask "product definition" is most critical because it determines to great extent the boundaries of following tasks and the overall result of the study – providing eco-design requirements.
Prodcom will be the first basis for defining the product, since Prodcom allows for precise and reliable calculation of trade and sales volumes in task 2. If the product definition relevant from a technical, economic and environmental point of view does not match directly with one or several Prodcom categories, the study will detail how it is translated into one or several Prodcom categories (or parts of Prodcom categories).
The above existing categorizations are a starting point for defining the product and can be completed by other relevant definition criteria, such as the functionality of the product, its environmental characteristics and the structure of the market where the product is placed (e.g. users, distribution channels or supply chain).
In particular, the definition of the product will also be linked to the assessment of the primary product performance parameter (the "functional unit").
If needed, on the basis of functional performance characteristics and not on the basis of technology, a further segmentation can be applied on the basis of secondary product performance parameters.
The product definition will also take into account whether the product interacts with the installation/ system in which it operates, which may imply:

- that the possible effects of the product being part of a larger system and/ or installation are identified and evaluated regarding environmental impacts and potential for improvement

or

- that the system should be considered as a product, including some parts or incorporating some components, and sub-assemblies as referred to in Article 2 of the Ecodesign Directive.

The suggested product definition will be confirmed by a first screening of the volume of sales and trade, environmental impact and potential for improvement of the product as referred to in Article 15 of the Ecodesign Directive.
Also information on standards, regulations, voluntary agreements and commercial agreements on EU, MS and 3rd country level should be considered when defining the product(s).

1.5.2 Product categories found in PRODCOM

PRODCOM is a system for the collection and dissemination of statistics on production of manufactured goods. It is based on a product classification called the PRODCOM list. It originates from the Europroms [7] -Prodcom [8] statistics database. For distribution transformers it is subdivided according to technology and rated power. Power transformers are subdivided according to their voltage rating.

The PRODCOM classification for transformers is presented in Table 1-1.

Prodcom Code	Description
31.10.41.30	Liquid dielectric transformers having a power handling capacity ≤ 650 kVA
31.10.41.53	Liquid dielectric transformers having a power handling capacity > 650 kVA but ≤ 1 600 kVA
31.10.41.55	Liquid dielectric transformers having a power handling capacity > 1 600 kVA but ≤ 10 000 kVA
31.10.41.70	Liquid dielectric transformers having a power handling capacity > 10 000 kVA
31.10.42.35	Other transformers, nes, power handling capacity ≤ 1 kVA
31.10.42.55	Other transformers, nes, 1 kVA < power handling capacity ≤ 16 kVA
31.10.43.30	Transformers, nes, 16 kVA < power handling capacity < 500 kVA
31.10.43.50	Transformers, nes, power handling capacity > 500 kVA

Table 1-1: PRODCOM categorization for transformers

Remarks:
- PRODCOM already subdivides the products according to one performance parameter, its rated power.
- PRODCOM already subdivides the products according to one technological property, liquid or non liquid dielectric transformers.

1.5.3 Subcategories according to the rated power

Transformers are rated based on the apparent power (S) input to the transformer – including its own absorption of active and reactive power (see also definition in section 1.6). Subcategories based on rated power were already defined in PRODCOM, see section 1.5.2. For any new subcategory defined hereafter new minimum and maximum rated values will have to be derived from related product standards and/or market data.

1.5.4 Subcategories of transformers according to the technology

Transformers can be further subcategorized based on material technological properties. PRODCOM already subdivides the products according to one technological property,

[7] Europroms is the name given to published Prodcom data. It differs from Prodcom in that it combines production data from Prodcom with import and export data from the Foreign Trade database.
[8] Prodcom originates from the French "PRODuction COMmunautaire"

liquid or non liquid dielectric transformers. This subcategory is related to the type of cooling medium. Using the product bill of materials, further technological subcategories can be defined by the material used for the coil windings (aluminium, copper) or core (silicon steel, amorphous steel).

Hereafter is a short description of these subcategories. Please note that it is not the purpose to perform a full analysis here in the report neither to enter in the full details of each defined subcategory (e.g. grain oriented vs non grain oriented silicon steel). The detailed technical analysis of the subcategories will be done in tasks 4 and 5.

Figure 1-5 Liquid dielectric transformer

Short description of liquid dielectric transformers, also called liquid-immersed transformers or liquid transformers or oil cooled transformers
Liquid transformers (Figure 1-5) rely on oil or another liquid circulating around the coils for cooling. Liquid removes heat more effectively than air. Liquid filled transformers are smaller in size than dry-type units for the same power rating capacity and have lower losses due to their smaller dielectric distances. However, many liquids used in transformers are flammable and some older types were toxic.
The identification of the cooling method for oil cooled transformers is expressed by a four-letter code. The first letter expresses the internal cooling medium in contact with the windings. The second letter identifies the circulation mechanism for internal cooling medium. The third letter expresses the external cooling medium. The fourth letter identifies the circulation mechanism for external cooling medium. The following cooling methods exist:

- ONAN: Oil Natural Air Natural
- ONAF: Oil Natural Air Forced
- OFAN: Oil Forced Air Natural
- OFAF: Oil Forced Air Forced
- OFWF: Oil Forced Water Forced

Other combinations are also possible.

Short description of non liquid dielectric transformers

Figure 1-6 Dry-type transformer

Non liquid or *Dry-type transformers* (Figure 1-6) use the natural convection of air for insulation and cooling. Dry-type transformers are divided into different temperature classes which are related to maximum permitted temperature increases of the transformer windings (e.g. temperature class H corresponds to a max operating temperature of 180°C). Dry-type transformers are commonly used in large industrial units, airports, large buildings and wind turbines.

In large power transformers (>25 MVA) gas-filled transformers exist but are seldom used in Europe (less than 100 according to ORGALIME). Only one UK utility is in the process of installing 275kV, 150 MVA units with associated 33/11 kV at 33.8 MVA units (Eurelectric (2010)). It is a transformer whose magnetic circuit and windings are enclosed with an insulating gas. Sulphur hexafluoride (SF6) gas is generally used. Such a transformer is sometimes referred to as a *gas-insulated transformer*.

1.5.5 Subcategories according to the type of service

Transformers are also classified in categories depending upon the type of service:

- **MV/LV Distribution transformers installed by DSO** refer to any transformer that takes voltage from a primary distribution circuit and "steps down" or reduces it to a secondary distribution circuit or a consumer's service circuit at e.g. 400 VAC or 230 VAC with an input voltage of at least 1.1 kV. Distribution transformers can vary in size, with the most common ranging from 50 kVA to 2.5 MVA, with an input voltage between 1.1 and 36 kV. (EN 50464-1). Distribution transformers are operated by the DSO (Distribution System Operator) or Utilities. Sometimes these transformers are also referred as *Utility transformers*. Those transformers are three phase transformers. International standards are developed within IEC/TC 14 and CENELEC CLC TC 14. Please note that a more specific parameter is the MV or LV rated voltage. In general the European continent uses three phase transformers and single phase transformers are not generally used in Europe. This is true on the continent but not in the UK and Ireland, the UK and Ireland (T&B consulting, 2010) have a requirement for about 10,000 to 15,000 single phase distribution transformers per annum. The grid in the UK and Ireland is more similar to the US with a larger amount of single phase transformers per group of a few houses.
- **DER LV/MV connecting transformers** are used to connect Distributed Energy Resources (DER) to the distribution grid, e.g.: wind turbines, photovoltaic, fuel cells,.. They might be designed with higher rated power than Distribution

transformer (especially for wind turbines). Those transformers might also be optimized for a particular load profile and shape for integration (e.g. wind turbine). International standards are developed within IEC/TC 14 and standard IEC 60076-16 is in progress.

- **MV/LV distribution transformers installed by non DSO (industry, ..)** are used by the industry to purchase electricity at high voltage (HV) or medium voltage (MV) grid and step it down for use on site at Low Voltage (230/400 VAC). The size of industrial transformers is higher compared to distribution transformers. These transformers connect to the DSO. Also the tertiary sector (e.g. large retailer stores, office buildings, ..) frequently installs these transformers. They range from 100 kVA until 4 MVA. Please note that smaller industrial consumers are connected to the distribution grid and transformers. International standards are developed within IEC/TC 14 and CENELEC CLC TC 14. Sometimes these transformers are also referred as *Industry transformers*.
- **LV/LV distribution autotransformers installed by DSO** have a secondary voltage which is higher than the primary voltage but both voltages are within the LV limit (≤1000 VAC). They can be installed as **line voltage restorers** in the 230 VAC distribution grids, typical in rural grids with long distribution lines and few users. These transformers are so-called autotransformer; it is a transformer with primary and secondary windings that have a common part. The size ranges from one single connection (10 kVA) until the minimum distribution transformer (50 kVA). Transformers can be single or three phase. Please note that this is a very different products group because standards are developed within IEC/TC 96 and the products are not made by distribution transformer manufacturers. It has been reported[9] that this is approach and problem is outdated, hence less relevant for this study. These products are also not frequently used anymore in grids, the main improvement is replacing the line that causes the voltage drop with related losses not to fix the problem with an autotransformer. There is little or no information on their performance. As a consequence it is proposed to leave them out of scope, as mentioned earlier they can be clearly discriminated by the LV definition and there is no risk for loopholes.

Figure 1-7 Power transformer

- **Power transformers installed by TSO (DSO) or power plant owner** (Figure 1-7) refer to those transformers used between the generator and the distribution circuits and are usually rated at 5 to 1500 MVA or even higher, with an input voltage mostly above 36kV. They are used in the MV and/or HV

[9] DEA

electrical grid. It ranges from the maximum size of 2 large distribution transformers (i.e. 5 MVA) until the largest power plant (about 500 MVA). Power transformers are available for step-up operation, primarily used at the generator and referred to as generator step-up (GSU) transformers, and for step-down operation, mainly used to feed distribution circuits. Power transformers are operated by the TSO (Transmission System Operator) or the generator (power plant owner). International standards are developed within IEC/TC 14. Sometimes these transformers are also referred as *Transmission system transformers*.

- **Phase-shifting power transformers.** Phase-shifting used in the high voltage grid with special vector groups to compensate for long transmission line electrical effects (phase lag) to control of active power flows in parallel transmission line systems. These transformers are discussed in standard IEC 62032 on 'Guide for the application, specification, and testing of phase-shifting transformers'. They have similar size as power transformers. International standards are developed within IEC/TC 14. Sometimes these transformers are also referred as *Transmission system transformers*.
- **Converter transformers used in HVDC** can be both in the range of power and distribution transformers as far as rated power and rated voltage are concerned. They are used with rectifiers to convert AC to DC or DC to AC with inverters. Converter transformers are typical used in High Voltage DC (HVDC) transmission. They have similar size as power transformers. They are a special category of power transformers. International standards are developed within IEC/TC 14 (IEC 61578-1).
- **Smaller industrial transformers** that are connected to the medium voltage system. These transformers are a niche product installed for various purposes in between the distribution transformer and the application. These transformers are used in low voltage (LV) systems which means that the High Voltage (HV) winding is **rated below or equal 1 kV**. Therefore the smaller transformers defined hereafter can easily be discriminated from previous categories. Several subcategories are described hereafter.

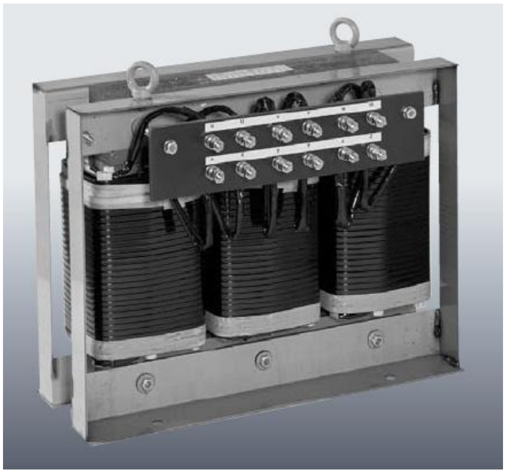

Figure 1-8 Separating transformer 3-phase

a. **Smaller industrial transformers used in industrial LV electricity distribution.** Please note that although the technical similarities this is a very different products group because the standards are developed within IEC/TC 96 and these products are not made by distribution transformer manufacturers**.** Identified categories are:

i. **Separating transformer**: Is a transformer that has primary and secondary windings electrically isolated by means of basic insulation (Figure 1-8), so as to limit, in the circuit fed by the secondary winding, the risks in the event of accidental simultaneous contact with earth and live parts. Typical size for three phase transformers is from 1 kVA up to 63 kVA. Please not that this is not common practice in industry and they are only used in cases of strong safety and availability requirements.

ii. **Isolating transformer:** Is a separating transformer that has primary and secondary windings electrically isolated by means of double or reinforced insulation. Frequent applications are a change of earthing system or a critical load protection in distorted systems. Typical size for three phase transformers is from 1 kVA up to 63 kVA. Please not that this is not common practice in industry and they are only used in cases of severe electromagnetic compatibility requirements (e.g. also in medical equipment).

iii. **Control transformer:** These transformers have at least a basic isolation between primary and secondary windings and are required for power supplies in machine control circuits (cf. EN 60 204 – 1), e.g. for powering small motors or instrumentation equipment. The typical secondary voltage is 24 VAC. Those are most often single phase transformers from 40 VA until 2.5 kVA. Please note that these transformers are nowadays being replaced by electronic power supplies as a consequence of using PLC (programmable logic control) instead of formerly electro mechanic relays in industrial control applications. Nevertheless those transformers might still be available on the market.

b. **Smaller industrial transformers used with industrial applications:**

i. **Safety transformers** used to supply safety extra low voltage (SELV) circuits (safety voltage ≤ 50 V) with an external power supply. Those are most often single phase transformers from as little as 0.6 VA. Please note that such transformers with a power supply up to 250 W were already studied in the finalized lot 7 Preparatory Study on 'External Power Supplies and Battery Chargers[10]'

ii. **Special transformers incorporated in industrial equipment.** In many cases the electrical power is transformed within the industrial equipment similar to much household equipment (TVs, ICT, ..). Some known applications are welding equipment, corona treatment equipment, DC power supplies, ..It should also be assessed if the improvement potential is at transformer level or within the system or application. US NAICS (North American Industry Classification System) Code 335311 (Power, Distribution, and Speciality Transformer Manufacturing) which names fluorescent lamp ballasts, machine tools, high-intensity light transformers, electric furnaces, rectifiers, and ignition systems as other examples of specialty transformers.

c. **Smaller transformers used in or with consumer products: (LV-LV AC to AC or LV-LV AC to DC).** They are mentioned here for the sake of completeness. Many small transformers are used for power supply units of appliances, electronic devices and UPS. They are addressed in the Ecodesign Directive context together with the related products. For more information the product related Ecodesign studies should be consulted.

[10] http://www.ecocharger.org/

Please note that although the technical similarities these smaller industrial transformers are a very different products group because the standards are developed within IEC/TC 96 or other product or application standards. These products are not made by distribution transformer manufacturers. The smaller transformers themselves are all technical very similar, the difference is often only in the insulation layer between the primary and secondary winding and the output voltage in the case of a control transformer.

1.5.6 Any other functional subcategories of transformers not defined before

Depending on the wiring transformers can be either *three phase* or *single phase* transformers. Single phase are worth mentioning but they are in Europe not a significant volume, these can be found in Japan or US but they have a different distribution system due to lower line voltage (110 VAC).

One can discriminate *pole* and *non pole mount* distribution transformers. This aspect is especially dealt with in Task 7 on policy recommendations.

Oil filled transformers with *biodegradable* or *synthetic oil*.
For energy efficiency please consult the section on standards.

1.5.7 Proposed scope of this study and first screening of the results

When defining the system boundaries, the following elements should be taken into account:

- To define transformers with similar characteristics, e.g. type of technology and apparent power, in order to be able to derive meaningful conclusions regarding design options, improvement potential and finally potential policy options in later tasks or chapters.
- To define and identify product groups, e.g. type of service and application (industry, household,..), suitable for later legislation, the preference is given to product boundaries connected to technical performance parameters. The definition of product groups solely on the basis of application without clear verifiable technical parameters might create loopholes if the proper incentives or installation requirements are missing.

Table 1-2 summarizes the major previously defined product subcategories and their relation to the type of service, sector of application, technology used, functionality and typical rated power (S).

Table 1-3 and Table 1-4 contain the first screening of the volume of sales and trade, environmental impact and potential for improvement of these product subcategories as referred to in Article 15 of the Ecodesign Directive.

Table 1-3 in particular includes the first screening on potential annual energy savings per product subcategory. The table compares the estimated annual Electricity Energy use (TWh) for 2005 and the projected Electricity use (TWh) in the assumption that only very efficient products with BAT (Best Available Technology) are used. Please note that a more detailed analysis will be done in the later tasks. The first rough estimated impact of smaller industrial transformers is very low (<0.3 TWh). This is in line with the findings of the Australian MEPS study[11]; it concluded 'Small transformers with rating less than 10 kVA single phase are too small for general electrical distribution applications. As explained before they are often used for more specific power supply applications (e.g. SELV, isolation, separation, ..)... Thus they would not contribute significantly to total EU 27 energy saving. Nevertheless it is proposed to include those to the extend possible within this study.

For the other environmental impacts (see Table 1-4) rough estimates codes are added that indicate the importance for the related product: H (High), M (Medium) and L (Low), while N stands for not applicable. The last column indicates expected trends comparing when BAT with average energy efficient products, herein stand a '+' for expected improvement while a '-' for potential negative impact and '0' means no expected impact.

The market data for the first screening was mainly those obtained from contacting T&D Europe (ORGALIME) members and other stakeholder comments on this chapter, a more detailed analysis on market data is in Task 2. More details on the improvement options will be discussed in Tasks 5, the first assessment was done based on the best classes included in related standards (see also the related section in this Task report). The complementary spreadsheet for calculating the tables can be found on the project website.

Proposed scope of the study:

The scope are power transformers used in transmission and distribution of electric power. This means that power transformer should be understood as transformer for the purpose of transmitting electrical power at EU27 grid frequency and voltage levels at power levels above 1 kVA single phase and 5 kVA poly phase. Special transformers incorporated in industrial equipment should be excluded, such as instrument transformers, testing transformers, welding transformers

Table 1-2 gives an overview of the transformer categories. It is proposed to include the transformers with green background and to exclude transformers with grey background for detailed technical analysis in tasks 2-6, however they will be reconsidered again in task 7 when discussing the scope of policy measures.

[11] Technical report "Distribution Transformers: Proposal to increase MEPS Levels" http://www.energyrating.gov.au/library/details200717-meps-transformers.html

			Main Type of Technology used or Functionality												
Study scope	Major subcategory name	Type of Service and Sector	Oil cooled	Dry-type	Gas-filled	MV/LV	HV and/or MV	Phase change	LV/LV	Copper winding	Aluminium winding	Amorphous steel core	S Min (kVA)	S Max (kVA)	S Avg (kVA)
y	**MV/LV Distribution transformer**	Distribution by DSO	99.99%	0.01%		100%				90%	10%	<100	50	2500	250
n	**line voltage restorers**	Distribution by DSO		100%					yes	100%			10	50	25
y	**DER LV/MV transformers**	Connecting DER by producer	20%	80%		100%				80%	20%	0%	50	2500	2000
y	**Industry MV/LV oil transformer**	Distribution by non DSO (industry, ..)	50%			100%				85%	15%		50	2500	630
y	**Industry MV/LV dry transformer**	Distribution by non DSO (industry, ..)		50%		100%				15%	85%		50	4000	800
y	**Power transfomer**	Power by TSO (DSO)	100%		0%		99%			100%			5000	>	1E+05
y	**Phase shifter**	Power by TSO (DSO)	100%		0%			1%		100%			5000	>	1E+05
y	**Seperation/isolation transformer**	Distribution by non DSO (industry, ..)		100%						100%			1	63	16
y/n	**Control transformer**	Distribution by non DSO (industry, ..)		100%					yes	100%			0.04	2.5	1.6
n	**Safety transformers**	Specific ext. applications industry/domestic		100%					yes	100%			0.04	0.25	0.06
n	**speciality/consumer transformers**	Specific int. application industry/domestic	NA	NA		NA	NA		yes	NA	NA	NA	NA	NA	NA
n	**magnetic halogen transformers**	Lighting all sectors		100%					yes	100%			0.04	0.63	0.06

Acronyms used are:
LV: Low Voltage
MV: Medium Voltage
Pk: Load losses
Po: No load losses
DSO: Distribution System Operator
NA: Not Applicable
S: Rated Power

Table 1-2: Summary table on product categories of transmission and distribution transformers (green) and other non transmission and distribution transformers (grey)

Study scope	Major subcategory name	S Avg (kVA)	Stock 2005 (Kunits)	Annual sales (units)	Pk Avg sales 2005 (W)	Po Avg sales 2005 (W)	AF	Estimated TWh (EU27 in 2005)	Pk BAT (W)	Po BAT (W)	AF	Potential TWh (EU27 if all BAT)
y	**MV/LV Distribution transformer**	250	3600000	140400	3250	650			2350	300		
n	**line voltage restorers**	25	36000	NA	NA	NA		0.0	NA	NA	NA	0.0
y	**DER LV/MV transformers**	2000	20000	2900	NA	NA			NA	NA	NA	
y	**Industry MV/LV oil transformer**	630	800000	43200	6500	1300			4600	600		
y	**Industry MV/LV dry transformer**	800	170000	8047	10000	2500			6500	1600		
y	**Power transfomer**	1E+05	64400	1803	300000	80000			260000	28000		
y	**Phase shifter**	1E+05	650	17	300000	80000			260000	28000		
y	**Seperation/isolation transformer**	16	7500000	75000	750	110	0.12		450	110	0.12	
y/n	**Control transformer**	1.6	merged	merged	merged	-	-		-	-	-	
n	**Safety transformers**	0.06	20000000	6000000	6	6	0.12	0.2	9	7.5	0.12	0.1
n	**speciality/consumer transformers**	NA	NA	NA	NA	NA	NA	0	NA	NA	NA	0.0
n	**magnetic halogen transformers**	0.06	1E+08	6000000	6	6	0.08	0.8				0.6

Acronyms used are:

LV: Low Voltage
MV: Medium Voltage
Pk: Load losses
Po: No load losses
DSO: Distribution System Operator
NA: Not Applicable
S: Rated Power
BAT: Best Available Technology
AF: Availability Factor

Table 1-3: Summary Table with first impact screening of Annual Electricity Energy use (TWh) estimated for 2005 and projected Electricity use (TWh) in the assumption of all BAT products (Note: these values impact values are updated in later chapters)

Study scope	Major subcategory name	Impact parameters related to production/EoL	Noise	EMF	Hzardous materials (oil)	Impact parameters related to production/EoL	Noise	EMF	Hzardous materials (oil)
		rel.	rel.	rel.	rel.	Trend	Trend	Trend	Trend
y	**MV/LV Distribution transformer**	M	M	M	M	-	?	+	-
n	**line voltage restorers**	M	N	N	N	0	0	0	0
y	**DER LV/MV transformers**	M	M	L	M	-	?	?	0
y	**Industry MV/LV oil transformer**	M	N	N	N	-	?	?	-
y	**Industry MV/LV dry transformer**	M	L	L	M	-	?	?	0
y	**Power transfomer**	M	L	L	M	-	0	0	-
y	**Phase shifter**	M	L	L	M	-	0	0	-
y	**Seperation/isolation transformer**	M	L	L	N	-	?	+	0
y/n	**Control transformer**	M	L	L	N	-	?	0	0
n	**Safety transformers**	M	L	L	N	-	+	+	0
n	**speciality/consumer transformers**	M	?	?	?	?	?	?	?
n	**magnetic halogen transformers**	H	M	L	M	-	+	+	0

Acronyms used are:
LV: Low Voltage
MV: Medium Voltage
Pk: Load losses
Po: No load losses
DSO: Distribution System Operator
NA: Not Applicable
S: Rated Power
BAT: Best Available Technology
AF: Availability Factor
EMF: ElectroMagnetic Fields

Table 1-4:Non Energy related first impact screening per major subcategory

1.6 Performance specification parameters

The proposed primary transformer performance parameter is 'Transformer rated power' (S).

Transformer rated power is defined as a conventional value of apparent power, establishing a basis for the design of a transformer, the manufacturer's guarantees and the tests, determining a value of the rated current that may be carried with rated voltage applied, under specified conditions (IEC 60050).
The interpretation of rated power according to IEC 60076-1 (§4.1) implies that it is a value of apparent **power input** to the transformer, including its own absorption of active and reactive power.

Proposed secondary functional transformer performance parameters related to energy efficiency and connected to *the transformer application*:

- *Load Factor (α)* (=Pavg/S) the ratio of the energy generated by a unit during a given period of time to the energy it would have generated if it had been running at its maximum capacity for the operation duration within that period of time (IEC 60050). The load factor of a transformer is defined as the ratio of the average load in active power to the rated power (S) of the transformer during a given periode of time.
- *Load losses (Pk)*: the absorbed active power at rated frequency and reference temperature, associated with a pair of windings when rated current is flowing through the line terminals of one of the windings, and the terminals of the other winding are short-circuited. Further windings, if existing, are open-circuited. (IEC 60076-1)
- *Auxiliary losses (Paux)*: the active power needed for the auxiliary components of the transformer (e.g. fans, pumps…).

Proposed secondary functional transformer performance parameters related to energy efficiency and connected to *the transformer application*:

- *Load Factor (α)* (=Pavg/S) the ratio of the energy generated by a unit during a given period of time to the energy it would have generated if it had been running at its maximum capacity for the operation duration within that period of time (IEC 60050). The load factor of a transformer is defined as the ratio of the average load to the rated power (S) of the transformer.
- *Load form factor (Kf)*: the ratio of the root mean squared (rms) Power to the average Power (=Prms/Pavg)
- *Transformer availability factor (AF)* determines the availability of the transformer on a given instant of time (mostly on a yearly basis).
- *Power factor (PF)*: the ratio of the active power (kW) to the apparent power (kVA).
- *K-factor*: this is a derating factor for a standard transformer used to supply non-linear loads, so that the total loss on harmonic load does not exceed the fundamental design loss of the transformer. For these applications, specially constructed or K-rated transformers should be used (EN 50464-3).

Other relevant performance parameters mainly used for *functional transformer selection*:

- *Volume and dimensions* of the transformer (SI units).
- *Weight* of the transformer (SI units).
- *Short-circuit impedance* (of a pair of windings) IEC 60076-1 : the equivalent series impedance (Z=R+jX), in Ohms, at rated frequency and reference temperature, across the terminals of one winding of a pair, when the terminals of the other windings, if existing, are open-circuited. For a three-phase transformer the impedance is expressed as phase impedance (equivalent star

connection). This quantity may be expressed in relative, dimensionless form, as a fraction z of the reference impedance Zref, of the same winding of the pair. In percentage notation:

$z = 100 * Z/Z_{ref}$

Where $Z_{ref} = U^2/Sr$

U is the voltage of the winding to which Z and Z_{ref} belong
Sr is the reference value of rated power

- *Rated voltage of the high-voltage winding (Vrms) (HV)*: the rated rms voltage of the high-voltage winding of the transformer (IEC 60076-1)
- *Rated voltage of the low-voltage winding (Vrms) (LV)*: the rated rms voltage of the low-voltage winding of the transformer (IEC 60076-1)
- *LwA in dB (A)*: Sound pressure level of the transformer. If the "A weighting filter" is used, the sound pressure level is given in units of dB(A) or dBA. Sound pressure level on the dBA scale is easy to measure and is therefore widely used. To determine the loudness of a sound, one needs to consult some curves representing the frequency response of the human ear.
- *Vector group*: The vector group provides a simple way of indicating how the internal connections of a particular transformer are arranged. The vector group is indicated by a code consisting of two or three letters, followed by one or two digits. In the IEC vector group code, each letter stands for one set of windings. The HV winding is designated with a capital letter, followed by medium or low voltage windings designated with a lowercase letter. The digits following the letter codes indicate the difference in phase angle between the windings, with HV winding taken as a reference. The number is in units of 30 degrees. For example, a transformer with a vector group of Dy1 has a delta-connected HV winding and a wye-connected LV winding. The phase angle of the LV winding lags the HV by 30 degrees.
- *Insulation temperature class*: The insulation temperature classes determine the maximum operating temperature of the transformer. IEC 60085 defines six temperature classes: A (105°C), E (120°C), B (130°C), F (155°C), H (180°C) and C (220°C). This is for insulation material in dry type transformers, not liquid.
- *Protection class (IP)*: provides a protection rating for the enclosure of the transformer. It is indicated as IP followed by two digits, the first digit (0…6) represents protection against ingress of solid objects, the second digit (0…8) represents protection against ingress of liquids. (EN 60529).
- *Fire behaviour class*: IEC 60076-11 (Dry type transformers) defines three fire behaviour classes: F0 (transformer suitable for being used in an environment without fire risk), F1 (self-extinguishing) and F2 (by means of special provisions, the transformer shall be able to operate for a given time period if subject to an external fire).
- *Environmental class*: with regard to humidity, condensation and pollution, IEC 60076-11 (Dry type transformers) defines three different environmental classes: E0 (clean and dry environment); E1 (presence of occasional condensation and limited pollution); E2 (frequent condensation or heavy pollution or combination of both).
- *Climate class*: with regard to the minimum ambient temperature to which transformers can be exposed, the following climatic classes are defined (IEC 60076-11): C1 (transformer suitable for being used with ambient temperature up to -5°C, the transformer can be exposed during transport and storage to ambient temperatures down to – 25°C); C2 (transformer suitable for operation, transport and storage at ambient temperatures down to -25°C)

Remark: *Rated values* are conventional values, guaranteed by the manufacturer under specified conditions (e.g. as specified in an IEC/EN standard). *Nominal values* are suitable approximate values.

1.6.1 Functional unit for transformers

Knowing the functional product used in this study, we can now further explain what is called the "functional unit" for transformers. In standard 14040 on life cycle assessment (LCA) the functional unit is defined as "the quantified performance of a product system for use as a reference unit in life cycle assessment study". The primary purpose of the functional unit in this study is to provide a calculation reference to which environmental impacts (such as energy use), costs, etc. can be related to, and to allow for comparison between functionally equal products with and without improvement options. Please note that further product segmentations will be introduced in this study in order to allow appropriate equal comparison.

Different functional units have been used in previous studies for such transformers:

- Functional unit used for the LCA[12] of Power transformer TrafoStar 63 MVA was 1 MVA of the system apparent power.
- Functional unit used for the LCA[13] of Power transformer 16/20 MVA was 1 kVA of the system apparent power.
- A LCA study of current transformers[14] used the functional unit as to deliver 1 kWh electricity for all material and energy flows allocated to 40 years use of a transformer

There is a link between both system apparent power and transformed energy using the transformer load factor (see also Task 3), the transformer load factor is connected to the application.

Proposal for functional unit: 'Transformer rated power' (S) (unit is 1 kVA).

Rationale: This proposal could provide a product evaluation at the stage of production making different assumptions on the application or putting into service.

1.7 Test and other standards

Scope:
The first aim of this subtask is to give an overview of existing measurement or test standards and associated test methods for power and distribution transformers considered and to identify needs and requirements for new standards to be developed.
These measurement and test standards or procedures are essential for future legislation, because they allow quantifying the product performance.
Finally the second aim is to describe the other standards for the product.

[12] Environmental Product Declaration of Power transformer TrafoStar 63 MVA, http://library.abb.com/global/scot/scot292.nsf/veritydisplay/4af3f4e6a43df7aec1256d630042c2fc/$File/ProductDeclarationStarTrafo63.PDF

[13] Environmental Product Declaration power Transformer 16/20 MVA, http://www.environdec.com/reg/e_epd56.pdf

[14] LCA study of current transformers, DANTES project co-funded by the EU Life-Environment Program, http://www.dantes.info/Publications/Publication-doc/DANTES%20ABB%20LCA%20study%20of%20instrument%20transformers.pdf

Please note that in task 7.1, where appropriate, proposals for needs or generic requirements for harmonized standards will be confirmed.
A complementary study of the existing test and measurement standards for small transformers is also incorporated (see section 1.7.2).

Background information on European and International standardization bodies:
EN/CENELEC internal regulations define a standard as a document, established by consensus and approved by a recognized body that provides, for common and repeated use, rules, guidelines or characteristics for activities or their results, aimed at the achievement of the optimum degree of order in a given context. Standards should be based on consolidated results of science, technology and experience, and aimed at the promotion of optimum community benefits. The European *EN* standards are documents that have been ratified by one of the three European standards organizations, CEN, CENELEC or ETSI.
In addition to "official" standards, there may be other sector specific procedures for product testing, which could be considered as standards when they have been recognized both by the sender and the receiver, that is, when they are using the same parameters or standards. Those procedures are discussed later in this chapter.
Following the EU's 'New Approach', any product-oriented legislation should preferably refer to harmonized (EN) test standards in order to verify the compliance with set measures. The referenced test standard should be accurate, reproducible and cost-effective, and model as well as possible the real-life performance. If no suitable test standard exists, they need to be developed (possibly based on existing sector specific procedures) for the relevant parameters in the view of implementing measures.
In technical use, a standard is a concrete example of an item or a specification against which all others may be measured or tested.
In the context of this study most of the EN standards are equivalent to IEC standards (EN 6xxxx –series of standards). Nevertheless it is also possible to have CENELEC and EU27 national standards that are not derived from IEC (e.g. EN 50464 described in 1.7.1.2.1). *IEC* is an acronym for the International Electro technical Commission. Power and distribution transformer standards are developed within Technical Committee 14 (IEC/TC14) on 'Power transformers'. European technical experts are directly delegated directly within IEC/TC 14. Standards for small power transformers, reactors and power supply units are developed by IEC/TC 96.
In the US and some other countries standards are developed within the IEEE. IEEE is an acronym for the Institute of Electrical and Electronics Engineers. *IEEE* are not de facto equivalent to IEC standards, they are developed in parallel.
Please note that it is also possible to have national standards in Europe as far as they do not conflict with the harmonized standards.

1.7.1 Power and distribution transformers (T&D sector)

1.7.1.1 List of CENELEC (TC14) standards and documents

Different types of documents are available:

- Standards (EN-xxxxx): The EN-50000 to -59999 covers CENELEC activities and the EN-60000 to -69999 series refers to the CENELEC implementation of IEC documents with or without changes
- Technical Reports (TR): A Technical Report is an informative document on the technical content of standardization work. Only required in one of the 3

official languages, a TR is approved by the Technical Board or by a Technical Committee by simple majority. No lifetime limit applies

- Harmonization Documents (HD): Same characteristics as the EN except for the fact that there is no obligation to publish an identical national standard at national level (may be done in different documents/parts), taking into account that the technical content of the HD must be transposed in an equal manner everywhere

1.7.1.1.1 EN-50xxx standards

EN 50195:1996
Code of practice for the safe use of fully enclosed askarel-filled electrical equipment
EN 50216-1:2002
Power transformer and reactor fittings -- Part 1: General
EN 50216-2:2002/A1:2002
Power transformer and reactor fittings -- Part 2: Gas and oil actuated relay for liquid immersed transformers and reactors with conservator
EN 50216-3:2002/A2:2006
Power transformer and reactor fittings -- Part 3: Protective relay for hermetically sealed liquid-immersed transformers and reactors without gaseous cushion
EN 50216-4:2002
Power transformer and reactor fittings -- Part 4: Basic accessories (earthing terminal, drain and filling devices, thermometer pocket, wheel assembly)
EN 50216-5:2002/A2:2005/A3:2006
Power transformer and reactor fittings -- Part 5: Liquid level, pressure and flow indicators, pressure relief devices and dehydrating breathers
EN 50216-6:2002
Power transformer and reactor fittings -- Part 6: Cooling equipment - Removable radiators for oil-immersed transformers
EN 50216-7:2002
Power transformer and reactor fittings -- Part 7: Electric pumps for transformer oil
EN 50216-8:2005/A1:2006
Power transformer and reactor fittings -- Part 8: Butterfly valves for insulating liquid circuits
EN 50216-9:2009
Power transformer and reactor fittings -- Part 9: Oil-to-water heat exchangers
EN 50216-10:2009
Power transformer and reactor fittings -- Part 10: Oil-to-air heat exchangers
EN 50216-11:2008
Power transformer and reactor fittings -- Part 11: Oil and winding temperature indicators
prEN 50216-12:2007
Power transformer and reactor fittings -- Part 12: Fans
EN 50225:1996
Code of practice for the safe use of fully enclosed oil-filled electrical equipment which may be contaminated with PCBs
EN 50299:2002
Oil-immersed cable connection assemblies for transformers and reactors having highest voltage for equipment Um from 72,5 kV to 550 kV
EN 50464-1:2007
Three-phase oil-immersed distribution transformers 50 Hz, from 50 kVA to 2 500 kVA with highest voltage for equipment not exceeding 36 kV -- Part 1: General requirements

EN 50464-2-1:2007
Three-phase oil-immersed distribution transformers 50 Hz, from 50 kVA to 2 500 kVA with highest voltage for equipment not exceeding 36 kV -- Part 2-1: Distribution transformers with cable boxes on the high-voltage and/or low-voltage side - General requirements
EN 50464-2-2:2007
Three-phase oil-immersed distribution transformers 50 Hz, from 50 kVA to 2 500 kVA with highest voltage for equipment not exceeding 36 kV -- Part 2-2: Distribution transformers with cable boxes on the high-voltage and/or low-voltage side - Cable boxes type 1 for use on distribution transformers meeting the requirements of EN 50464-2-1
EN 50464-2-3:2007
Three-phase oil-immersed distribution transformers 50 Hz, from 50 kVA to 2 500 kVA with highest voltage for equipment not exceeding 36 kV -- Part 2-3: Distribution transformers with cable boxes on the high-voltage and/or low-voltage side - Cable boxes type 2 for use on distribution transformers meeting the requirements of EN 50464-2-1
EN 50464-3:2007
Three-phase oil-immersed distribution transformers 50 Hz, from 50 kVA to 2 500 kVA with highest voltage for equipment not exceeding 36 kV -- Part 3: Determination of the power rating of a transformer loaded with non-sinusoidal currents
EN 50464-4:2007
Three-phase oil-immersed distribution transformers 50 Hz, from 50 kVA to 2 500 kVA with highest voltage for equipment not exceeding 36 kV -- Part 4: Requirements and tests concerning pressurized corrugated tanks
prEN 50XXX CLC/TC 14 (prEN: draft European Standard)
Environmental aspect in normal and abnormal operation
FprEN 50541-1:2009 (FprEN: Draft European Standard for Formal Vote)
Three phase dry-type distribution transformers 50 Hz, from 100 to 3 150 kVA, with highest voltage for equipment not exceeding 36 kV -- Part 1: General requirements and requirements for dry type transformers with highest voltage for equipment not exceeding 36 kV
prEN 50541-2
Three phase dry-type distribution transformers 50 Hz, from 100 to 3 150 kVA, with highest voltage for equipment not exceeding 36 kV -- Part 2: Determination of the power rating of a transformer loaded with non-sinusoidal current

1.7.1.1.2 EN 60xxx standards

EN 60076-1:1997/A1:2000/A12:2002
Power transformers -- Part 1: General
EN 60076-2:1997
Power transformers -- Part 2: Temperature rise for liquid-immersed transformers
FprEN 60076-2:2009
Power transformers -- Part 2: Temperature rise for liquid-immersed transformers
EN 60076-3:2001
Power transformers -- Part 3: Insulation levels, dielectric tests and external clearances in air
EN 60076-4:2002
Power transformers -- Part 4: Guide to the lightning impulse and switching impulse testing - Power transformers and reactors
EN 60076-5:2006
Power transformers -- Part 5: Ability to withstand short-circuit[15]

[15] M.J. Heathcote (2007): 'J&P Transformer Book', ISBN 978-0-7506-8164-3

The purpose is in relation to demonstrate short-circuit performance and that a transformer has adequate mechanical strength in its weakest position. It is an important standard, as it is a design challenge and a point of discussion on the technical feasibility of large amorphous core steel transformers. The performance of practical tests is difficult due to the enormous rating of test plant that is required. EN 60076, Part 5, deals with the subject of ability to withstand both thermal and mechanical effects of short circuit. There are separate headings for thermal and dynamic ability.
For thermal ability, the method of deriving the r.m.s value of the symmetrical short-circuit current is defined, as is the time for which this is required to be carried, and the maximum permissible value of average winding temperature permitted after short circuit (dependent on the insulation class). The method of calculating this temperature for a given transformer is also defined. Thus this requirement is proved entirely by calculation.
For the latter, it is stated that the dynamic ability to withstand short circuit can only be demonstrated by testing; however, it is acknowledged that transformers over 40 MVA cannot generally be tested. A procedure for testing transformers below this rating involving the actual application of a short Circuit is described. Oscillographic records of voltage and current are taken for each application of the short circuit and the assessment of the test results involves an examination of these, as well as an examination of the core and windings after removal from the tank. The Buchholz relay, if fitted, is checked for any gas collection. Final assessment on whether the test has been withstood is based on a comparison of impedance measurements taken before and after the tests. It is suggested that a change of more than 2 per cent in the measured values of impedance are indicative of possible failure.
This leaves a large group of transformers which cannot be tested. Although this is not very satisfactory, service experience with these larger transformers over a considerable period of time has tended to confirm that design calculations of the type described in the previous chapter are producing fairly accurate results. Careful examination of service failures of large transformers, especially where there may be a suspicion that short circuits have occurred close to the transformer terminals, can yield valuable information concerning mechanical strength as well as highlighting specific weaknesses and giving indication where weaknesses may be expected in other similar designs of transformer. For large important transformers which cannot be tested for short-circuit strength, there is no better method of assessing their capability than carrying out a critical review of manufacturers' design calculations questioning the assumptions made and seeking reassurance that these follow the manufacturers' own established practices proven in service. Where, by virtue of extending designs beyond previously proven ratings, it is necessary to make extrapolation, then such extrapolation should be clearly identified and the basis for this fully understood.
Important note: : the short circuit test standard in China is GBT-1094 Part 5 (instead of 1904), which is very similar to EN 60076-5. Therefore transformers tested in China can be assumed to pass the EN 60076-5 requirements as well.

EN 60076-6:2008
Power transformers -- Part 6: Reactors
EN 60076-7:2008
Power transformers -- Part 7: Loading guide for oil immersed power transformers
EN 60076-8: 1997
Power transformers – Part8: Application guide
EN 60076-10:2001
Power transformers -- Part 10: Determination of sound levels
EN 60076-11:2004
Power transformers -- Part 11: Dry-type transformers
EN 60076-13:2006
Power transformers -- Part 13: Self-protected liquid-filled transformers

FprEN 60076-16:2009
Power transformers -- Part 16: Transformers for wind turbines application
FprEN 61378-1:200X
Convertor transformers -- Part 1: Transformers for industrial applications
EN 60214-1:2003
Tap-changers -- Part 1: Performance requirements and test methods
EN 61378-1:1998
Convertor transformers -- Part 1: Transformers for industrial applications
EN 61378-2:2001
Convertor transformers -- Part 2: Transformers for HVDC applications

1.7.1.1.3 Technical Reports

CLC/prTR 50XXX
Three-phase substation transformers less than or equal to 170 kV and 100 MVA
CLC/TR 50453:2007
Evaluation of electromagnetic fields around power transformers
CLC/TR 50462:2008
Rules for the determination of uncertainties in the measurement of the losses on power transformers and reactors

1.7.1.1.4 Harmonization documents

HD 428.1 S1:1992/A1:1995
Three-phase oil-immersed distribution transformers 50 Hz, from 50 to 2500 kVA with highest voltage for equipment not exceeding 36 kV -- Part 1: General requirements and requirements for transformers with highest voltage for equipment not exceeding 24 kV
HD 428.3 S1:1994 CLC/TC 14
Three-phase oil-immersed distribution transformers 50 Hz, from 50 to 2500 kVA, with highest voltage for equipment not exceeding 36 kV -- Part 3: Supplementary requirements for transformers with highest voltage for equipment equal to 36 kV
HD 428.1 S1:1992
Three-phase oil-immersed distribution transformers 50 Hz, from 50 to 2500 kVA with highest voltage for equipment not exceeding 36 kV -- Part 1: General requirements and requirements for transformers with highest voltage for equipment not exceeding
HD 538.1 S1:1992/A1:1995
Three-phase dry-type distribution transformers 50 Hz, from 100 to 2500 kVA, with highest voltage for equipment not exceeding 36 kV -- Part 1: General requirements and requirements for transformers with highest voltage for equipment not exceeding 24 kV
HD 538.2 S1:1995
Three-phase dry-type distribution transformers 50 Hz, from 100 to 2500 kVA, with highest voltage for equipment not exceeding 36 kV -- Part 2: Supplementary requirements for transformers with highest voltage for equipment equal to 36 kV
HD 538.3 S1:1997
Three-phase dry-type distribution transformers 50 Hz, from 100 to 2500 kVA, with highest voltage for equipment not exceeding 36 kV -- Part 3: Determination of the power rating of a transformer loaded with non- sinusoidal current

The most relevant standards are explained below.

1.7.1.2 Most relevant test Standards on Energy Use and identified ecodesign parameters

Scope:
A "*test or measurement standard*" is a standard that sets out a test method, but that does not indicate what result is required when performing that test. Therefore, strictly speaking, a test standard is different from a "technical standard". Namely, in technical use, a standard is a concrete example of an item or a specification against which all others may be measured or tested. Often it indicates the required performance.
However, "test standards" are also (but not exclusively) defined in the "technical standard" itself. For example, an IEC standard for a certain product or process gives the detailed technical specifications, which are required in order to conform to this standard. It also defines test standards (or rather methods) to be followed for validating any such conformity. A standard can be either product or sector specific, and it can concern different stages of a product's life cycle.

1.7.1.2.1 European (EN) Test Standards on Energy Use

Standards directly related to the environmental performance of transformers are relevant for this preparatory study and especially for power consumption testing.

EN 60076-1 (IEC 60076-1) 'Power transformers. General'
The 'IEC 60076-1' is the general generic standard for power transformers with European equivalent EN 60076-1. This general standard is applicable for power transformers (including auto-transformers) above 1 kVA single phase and 5 kVA poly phase. It contains requirements for transformers having a tapped winding, required information on the rating plate, the required tolerances on certain guaranteed values…

Paragraph 10 of the standard defines the requirements for routine, type and special tests:
Routine tests:

- Measurement of winding resistance (10.2)
- Measurement of voltage ratio and check of phase displacement (10.3)
- Measurement of short-circuit impedance and load-loss (10.4)
- Measurement of no-load loss and current (10.5)
- Dielectric routine tests (EN 60076-3)
- Tests on on-load tap-changers, where appropriate (10.8)

Type tests:

- Temperature rise test (EN 60076-2)
- Dielectric type tests (EN 60076-3)

Special tests:

- Dielectric special tests (EN 60076-3)
- Determination of capacitances windings-to-earth, and between windings
- Determination of voltage transfer characteristics
- Measurement of zero-sequence impedance(s) on three phase transformers (10.7)
- Short-circuit withstand test (EN 60076-5)
- Determination of sound levels (IEC 60551)
- Measurements of the harmonics of the no-load current (10.6)
- Measurement of the power taken by the fan and oil pump motors
- Measurement of insulation resistance to earth of the windings, and/or measurement of dissipation factor (tan δ) of the insulation system capacitances.

Load losses and no load losses are measured at factory ambient temperature, between 10°C and 40°C. During test the temperature rise must kept low by doing the test "quickly" (load losses) or before other tests (no load losses).
The results shall be corrected to a reference temperature: 75°C for oil-immersed transformers (EN 50464-1). For dry-type transformers the reference temperature is related to insulation temperature, e.g. for insulating temperature class F (155°C) the reference temperature would be 120°C (Fpr EN 50541-1).

The measuring system used for the test shall have certified traceable accuracy and be subjected to periodic calibration, according to the rules of ISO 9001. The required accuracy as such is not defined.
Table 1 of the standard defines tolerances for the transformer performance parameters. The maximum allowable tolerance for the total transformer losses (sum of the no-load loss and the load loss) is +10%. This means that in worst case the real transformer losses could be 10% higher than the losses specified by the transformer manufacturer.

Notes:

- TR50462:2008 defines the procedures and criteria to be applied to evaluate the uncertainty affecting the measurements of no load and load losses during the routine tests on power transformers.
- Industry experts reported that the accuracy of measurements in official laboratories are +/- 2 % and are reproducible. The procedures to carry out the measurements are clearly described without possibility to deviation.

EN 50464 series under the general title "Three-phase oil-immersed distribution transformers 50Hz, from 50 kVA to 2500 kVA with highest voltage for equipment not exceeding 36kV"

EN 50464-1 covers transformers from 50 kVA to 2500 kVA intended for operation in three-phase distribution networks, for indoor or outdoor continuous service, 50 Hz, immersed in mineral oil, natural cooling, with two windings:

- a primary (HV) winding with a highest voltage for equipment from 3.6kV to 36 kV;
- a secondary (LV) winding with a highest voltage for equipment not exceeding 1.1kV

Note: This standard may also be applied; either as a whole or in part, to transformers immersed in a synthetic insulating liquid.
The objective of this European standard is to lay down requirements related to electrical characteristics and design of three phase distribution transformers immersed in mineral oil. Performance parameters (load losses, no load losses) are specified at a given reference temperature (75°C). Tests must be done in accordance to test procedures defined in the EN 60076-x series standard.

Distribution transformers are subdivided into classes according to load (Pk) and no load (Po) losses per subcategory of transformer. For example, distribution transformers with a rated voltage of the High Voltage (HV) winding of $\leq$ 24 kV are divided into four classes for the load losses (A_k to D_k) and five classes for no-load losses (A_0 tot E_0).
The transformers with a rated voltage of the HV winding of 36 kV are divided into three classes for load and no-load losses (A_{036} to C_{036} and Ak_{36} to Ck_{36}). Most efficient transformers are labelled as A class.

In the tables below load and no-load losses for oil immersed distribution transformers with rated voltage of the HV-winding $\leq$ 24 kV are presented:

Load losses Pk (W) at 75 °C for Um ≤ 24 kV

Rated power	Dk	Ck	Bk	Ak	Short circuit impedance
KVA	W	W	W	W	%
50	1 350	1 100	875	750	4
100	2 150	1 750	1 475	1250	
160	3 100	2 350	2 000	1 700	
250	4 200	3 250	2 750	2 350	
315	5 000	3 900	3 250	2800	
400	6 000	4 600	3 850	3 250	
500	7 200	5 500	4 600	3 900	
630	8 400	6 500	5400	4600	
630	8 700	6 750	5 600	4 800	6
800	10 500	8 400	7 000	6 000	
1 000	13 000	10 500	9000	7 600	
1 250	16 000	13 500	11 000	9 500	
1 600	20 000	17 000	14 000	12 000	
2 000	26 000	21 000	18 000	15 000	
2 500	32 000	26 500	22 000	18 500	

No load Losses Po (W) and sound power level (Lw) for Um ≤ 24kV

Rated power	E0		D0		C0		B0		A0		Short circuit impedance
kVA	P0	LwA	P0	LwA	P0	LwA	P0	LwA	P0	LwA	%
	W	dB(A)	W	dB(A)	W	dB(A)	W	dB(A)	W	dB(A)	
50	190	55	145	50	125	47	110	42	90	39	4
100	320	59	260	54	210	49	180	44	145	41	
160	460	62	375	57	300	52	260	47	210	44	
250	650	65	530	60	425	55	360	50	300	47	
315	770	67	630	61	520	57	440	52	360	49	
400	930	68	750	63	610	58	520	53	430	50	
500	1 100	69	880	64	720	59	610	54	510	51	
630	1 300	70	1 030	65	860	60	730	55	600	52	
630	1 200	70	940	65	800	60	680	55	560	52	6
800	1 400	71	1 150	66	930	61	800	56	650	53	
1 000	1 700	73	1 400	68	1 100	63	940	58	770	55	
1 250	2 100	74	1 750	69	1 350	64	1150	59	950	56	
1 600	2 600	76	2 200	71	1 700	66	1450	61	1 200	58	
2 000	3 100	78	2 700	73	2 100	68	1800	63	1 450	60	
2 500	3 500	81	3 200	76	2 500	71	2150	66	1 750	63	

Please note that all combinations of load and no load classes can be found on the market, more detailed information on the market average will be included in chapter 2.

The efficiency of a transformer (EN 50464-1/6.1) is given for any load condition by the ratio between the output power (P2) and the input power (P1):

$\eta = 100.\ P2/P1$ (%)

Because of the difficulties to determine the efficiency by direct measurements, it can be evaluated conventionally through the measured losses as follows:

$$\eta = 100.\left(1 - \frac{\alpha^2.Pk + Po}{\alpha.S + \alpha^2.Pk + Po}\right) \ (\%)$$

Where:

Pk = Load losses at rated current and reference temperature
P0 = No load losses at rated voltage and frequency
S = Rated power
α = Load factor

The above mentioned formula is applicable for rated frequency; this means, in most cases, for a frequency of 50/60 Hz (Europe). This formula is applicable in the standard loading conditions of the transformer, this means that the load form factor (Kf), the power factor (PF), K-factor are not taken into account. It is also at the reference temperature.

HD 538.1 series under the general title "Three-phase dry-type distribution transformers 50 Hz, from 100 to 2500 kVA, with highest voltage for equipment not exceeding 36 kV"

The object of these documents is to lay down requirements related to electrical characteristics and design of three phases dry-type distribution transformers, therefore it assist the purchaser by using uniform tender specification

In the table below load and no-load losses for some dry-type distribution transformers with rated voltage of the HV-winding of 12 kV are presented:

Table HD538

	Load losses	No Load losses
	12 kV HV winding	12 kV HV winding
kVA	W	W
100	2000	440
160	2700	610
250	3500	820
400	4900	1150
630 /4%	7300	1500
630 /6%	7600	1370
1000	10000	2000
1600	14000	2800

Note: FprEN 50541-1:2009 (Final draft stage) will supersede HD538.1,S1: 1992 and HD 538.2, S1: 1995.

(Fpr)EN 50541-1 covers Three phase dry-type distribution transformers 50Hz, from 100 to 3150 kVA, with highest voltage for equipment not exceeding 36 kV (Part 1: General Requirements) (see Table 1-5 and Table 1-6).

Dry-type distribution transformers are subdivided into classes according to load (Pk) and no load (Po) losses per subcategory of transformer. For example, dry-type distribution transformers with a rated voltage of the High Voltage (HV) winding of $\leq$ 12 kV are divided into two classes for the load losses (A_k and B_k) and three classes for no-load losses (A_0, B_0 and C_0), whereas A class is the most efficient class.

The Load and no Load losses for dry type distribution transformers with rated voltage of the HV-winding of 12 kV as defined in HD538 matches with the B_kC_o class of the (draft) EN 50541-1 standard. For example, the load and load losses as defined in EN 50541-1 are respectively 4500W and 700W for the most efficient (A_kA_0) 400 kVA transformer.

Load loss, no load loss and sound power level

U_M	S_R	P_K	P_K	P_O	L_{WA}	P_O	L_{WA}	P_O	L_{WA}
		A_k	B_k	A_o		B_o		C_o	
kV	kVA	W	W	W	dB (A)	W	dB (A)	W	dB (A)
12	100	1 800	2 000	260	51	330	51	440	59
	160	2 600	2 700	350	54	450	54	610	62
	250	3 400	3 500	500	57	610	57	820	65
	400	4 500	4 900	700	60	880	60	1 150	68
	630	7 100	7 300	1 000	62	1 150	62	1 500	70
	800	8 000	9 000	1 100	64	1 300	65	1 800	71
	1 000	9 000	10 000	1 300	65	1 500	67	2 100	73
	1 250	11 000	12 000	1 500	67	1 800	69	2 500	75
	1 600	13 000	14 500	1 800	68	2 200	71	2 800	76
	2 000	15 500	18 000	2 200	70	2 600	73	3 600	78
	2 500	18 500	21 000	2 600	71	3 200	75	4 300	81
	3 150	22 000	26 000	3 150	74	3 800	77	5 300	83

NOTE 1 This European Standard applies also to transformers having Insulation System Temperature (IST) with temperature rise higher than IST of 180 °C; According to EN 60076-11:2004, Table 2; in this case the load losses will be calculated with proper temperature correction factors for rated temperature rises , for load loss guaranty and impedance voltage temperature reference (see 3.8).

Table 1-5: Example of proposed classes for dry-type transformers in prEN 50541-1 for ≤12kV dry-type transformers with 6% impedance voltage.

Table 5 - Load loss, no load loss and sound power level

U_M	S_R	P_K	P_K	P_O	L_{WA}	P_O	L_{WA}	P_O	L_{WA}
		A_k	B_k	A_o		B_o		C_o	
kV	kVA	W	W	W	dB (A)	W	dB (A)	W	dB (A)
24	100	1 800	2 050	280	51	340	51	460	59
	160	2 600	2 900	400	54	480	54	650	62
	250	3 400	3 800	520	57	650	57	880	65
	400	4 500	5 500	750	60	940	60	1 200	68
	630	7 100	7 600	1 100	62	1 250	62	1 650	70
	800	8 000	9 400	1 300	64	1 500	64	2 000	72
	1 000	9 000	11 000	1 550	65	1 800	65	2 300	73
	1 250	11 000	13 000	1 800	67	2 100	67	2 800	75
	1 600	13 000	16 000	2 200	68	2 400	68	3 100	76
	2 000	16 000	18 000	2 600	70	3 000	70	4 000	78
	2 500	19 000	23 000	3 100	71	3 600	71	5 000	81
	3 150	22 000	28 000	3 800	74	4 300	74	6 000	83

NOTE This European Standard applies also to transformers having Insulation System Temperature (IST) with temperature rise higher than IST of 180 °C; According to EN 60076-11:2004, Table 2; in this case the load losses will be calculated with proper temperature correction factors for rated temperature rises , for load loss guaranty and impedance voltage temperature reference (see 3.8).

Table 1-6 Example of proposed classes for dry-type transformers in prEN 50541-1 for 17.5 kV and 24 kV rated voltage dry-type transformers with 6% impedance voltage.

1.7.1.2.2 European (EN) Test Standards on other ecodesign parameters

Most of current test standards and legislations are related to energy efficiency, and thus to electricity consumption which has impact mainly on the environmental indicator Global Warming Potential. These standards were described in the previous section. However, this study does not focus on a specific environmental impact and on energy efficiency other ecodesign parameters were identified (see section 1.3). There might also be a relationship between energy efficiency and the other identified transformer performance parameters (see section 1.6).
The relationship with the other ecodesign parameter is included in Table 1-7.

Performance parameter or Ecodesign parameter	Standard	Status/notes	Gap identified
LwA dB (A): Sound pressure level of the transformer	IEC 60076-10 (EN)	Measurement method only	No
EMF (electromagnetic field)	EN 50413:2009	Recently adopted	No
Hazardous substances (PCB)	IEC 60296 (EN) – Mineral oil	PCB is forbidden by local legislation	No
Short-circuit impedance	IEC 60076-1 (EN)		No
Rated voltage of the high-voltage winding (Vrms)	IEC 60076-1 (EN)		No
Rated voltage of the low-voltage winding (Vrms):	IEC 60076-1 (EN)		No
Insulation temperature class	IEC 60085 (EN)		No
Protection class (IP)	IEC 60529 (EN)		No
Fire behaviour class	IEC 60076-11 (EN) - Dry type transformers only		No
Environmental class	IEC 60076-11 (EN) - Dry type transformers		No
Climate class	IEC 60076-11 (EN) - Dry type transformers		No

Table 1-7: Relationship between ecodesign parameter and test standards

Note:
This list is complete in the perception of transformer manufacturers associations ORGALIME (&SMA) and the Danish Energy Authority.
Standards on materials would not relate to the transformer product as such.

IEC 60905 (1987) Loading Guide for Dry-Type Power Transformers

This guide is applicable to naturally cooled dry-type power transformers. Six different insulation systems are taken into account, identified by their system temperatures.

Because there are numerous combinations of different insulation systems and constructions it is possible to make loading recommendations only of a general nature. For this reason the guide is in two parts:

- the first part makes no loading recommendations, but gives the method of calculating loading conditions when the variable parameters are known as the result of prototype testing of a particular construction and/or insulation system. The calculations are given in the form of an algorithm from which computer programs can be written;

- the second part assumes constant values for the variable parameters, with the exception of the insulation temperature limits (Table I) and the temperature of external cooling air, irrespective of insulation system or construction, thereby enabling load curves to be produced.

The guide indicates how dry-type transformers may be operated without exceeding the acceptable limit of deterioration of insulation through thermal effects. The acceptable limit of deterioration of insulation is defined as that which occurs when the dry-type transformer is operating under rated conditions at the basic temperature of the external cooling air.

1.7.1.3 Sector specific Test Standards

No, the IEC standard is used.

1.7.1.4 National Test Standards within EU27

In Germany, Power transformer designs for oil immersed power transformers with off-circuit tap-changer or with on-load tap-changer from 3150 kVA to 80 MVA for 50Hz and rated voltage up to 123kV, was laid down in DIN 42508:2009-08.
In the following table, no-load (“Leerlaufverluste “), load (Kurzschluβverluste) losses and sound power levels (“A-schall leistung”) are given as defined in DIN 425081 (2009. Note: In 2009 this standard was updated and contained about 10 % lower load losses compared to 1983.

Bemessungs-leistung S_r kVA	**Leerlauf-verluste** P_o kW		**Kurzschluss-verluste** P_k kW		**Bemessungskurzschluss-spannung** u_z % von U_r		**Schallleistung (Summe aus Leerlauf- und Lastgeräusch bei ONAN[a])** $L_{WA,IN}$ dB (A)
	a (≤ 36 kV)	b (> 36 kV)	a (≤ 36 kV)	b (> 36 kV)	a (≤ 36 kV)	b (> 36 kV)	
3 150	2	–	20	–	6	–	53
4 000	3	–	30	–	6	–	55
5 000	3	–	40	–	7	–	56
6 300	4	6	45	55	7	10	63
8 000	4	6	50	60	7	10	66
10 000	4	7	52	62	7	10	71
12 500	6	8	55	65	10	12	73
16 000	8	10	70	75	10	12	75
20 000	10	12	85	90	10	12	77
25 000	13	15	100	110	10	12	78
31 500	15	19	120	125	10	12	81
40 000	19	23	145	150	10	12	83
50 000	–	28	–	180	–	13	85
63 000	–	34	–	210	–	13	87
80 000	–	41	–	250	–	14	90

[a] Die Schallleistungen gelten bei Berücksichtigung der angegebenen Werte für P_o. Niedrigere Geräusche oder Verluste können vereinbart werden. Bei anderen Kühlungsarten als ONAN sind Abweichungen möglich. In diesem Fall werden die Geräuschwerte vor Auftragsvergabe zwischen Käufer und Hersteller festgelegt.

<u>Comparison of DIN for a small power transformers with EN50464 for a large oil-immersed distribution transformers extrapolated at 3150 kVA</u>:

A 3150 kVA power transformer from DIN425081(2009) can be extrapolated to 2500 kVA, this results in P0 = 1590 Watt (2000x2.5/3.150) and Pk 15900 Watt. As a consequence these DIN series power transformers would obtain classes A0Ak (<1750 Watt, <18500 Watt) and the DIN 425081(2009) is therefore ambitious.

For power transformers no other standards are used.

Else, the IEC standard is used.

1.7.1.5 Third country Test Standards and comparison

The above EN standards with IEC numbers are international standards.

As mentioned before the IEEE issues apart from the IEC standards. The equivalent standard for IEC 60076-1 (2000) is the IEEE C57.12.00 (2006) and IEEE C57.12.90. See also Annex A.

<u>Important note on 'rated power' (S) definition:</u> The interpretation of rated power according to IEC 60076-1 (§4.1) implies that it is a value of apparent **power input** to the transformer, including its own absorption of active and reactive power. This is different from the method used in transformer standards based on IEEE C57.12.00 where "rated kVA" is "**the output power** that can be delivered at….rated secondary voltage …".

1.7.1.6 Other relevant EU 27 national (EN) Standards or sector procedures

In Denmark common user spec is so-called 'DEFU' but that is strictly based on IEC, hence none.
ERDF refer in its tender procedures to the standards (norm.edf.fr document HN 52-S-20), they also specify to that the EN 50464-1 load classes should be on the name plate.

1.7.1.7 Other relevant Third country Standards or sector procedures

The equivalent IEC and IEEE standards are included in later sections.
Other countries are still welcome to provide information on equivalent standards.

1.7.2 Small transformers

Small transformers are technically similar to the larger power transformers. They are used in different kind of applications, e.g. in machine control circuits, toys, door bell, medical applications,.... In most of these applications the grid voltage (230Vac, 400Vac) is transformed to a lower (safety) voltage, e.g. 12Vac, 24Vac,… So these transformers are not as such part of the distribution networks.

Small transformers, but also reactors, power supply units, are within the scope of activity of CENELEC TC 96. Most of the applicable standards (EN-61558 series) are safety related.

The CENELEC TC 96 standards are listed below.

1.7.2.1 List of CENELEC TC 96 standards

EN 61558-1:2005/A1:2009 CLC/SR 96
Safety of power transformers, power supplies, reactors and similar products -- Part 1: General requirements and tests
EN 61558-2-1:2007 CLC/SR 96
Safety of power transformers, power supplies, reactors and similar products -- Part 2-1: Particular requirements and tests for separating transformers and power supplies incorporating separating transformers for general applications
EN 61558-2-2:2007 CLC/SR 96
Safety of power transformers, power supplies, reactors and similar products -- Part 2-2: Particular requirements and tests for control transformers and power supplies incorporating control transformers
EN 61558-2-3:2000 CLC/SR 96
Safety of power transformers, power supply units and similar devices -- Part 2-3: Particular requirements for ignition transformers for gas and oil burners
FprEN 61558-2-3:2008 CLC/SR 96
Safety of transformers, reactors, power supply units and similar products for supply voltages up to 1100 V -- Part 2-3: Particular requirements and tests for ignition transformers and ignition power supply units incorporating ignition transformers for gas and oil burners
EN 61558-2-4:2009 CLC/SR 96
Safety of transformers, reactors, power supply units and similar products for supply voltages up to 1 100 V -- Part 2-4: Particular requirements and tests for isolating transformers and power supply units incorporating isolating transformers
EN 61558-2-5:1998/A11:2004 CLC/SR 96
Safety of power transformers, power supply units and similar -- Part 2-5: Particular requirements for shaver transformers and shaver supply units
FprEN 61558-2-5:2008 CLC/SR 96
Safety of transformers, reactors, power supply units and similar products for supply voltages up to 1 100 V -- Part 2-5: Particular requirements and tests for shaver transformers, power supply units incorporating a shaver transformer and shaver supply units
EN 61558-2-6:2009 CLC/SR 96
Safety of transformers, reactors, power supply units and similar products for supply voltages up to 1 100 V -- Part 2-6: Particular requirements and tests for safety isolating transformers and power supply units incorporating safety isolating transformers
EN 61558-2-7:2007 CLC/SR 96
Safety of power transformers, power supplies, reactors and similar products -- Part 2-7: Particular requirements and tests for transformers and power supplies for toys
EN 61558-2-8:1998 CLC/SR 96
Safety of power transformers, power supply units and similar -- Part 2-8: Particular requirements for bell and chime transformers
FprEN 61558-2-8:2009 CLC/SR 96
Safety of transformers, reactors, power supply units and similar products for supply voltages up to 1100 V -- Part 2-8: Particular requirements and tests for bell and chime transformers
EN 61558-2-9:2003 CLC/SR 96
Safety of power transformers, power supply units and similar products -- Part 2-9: Particular requirements for transformers for class III hand lamps for tungsten filament lamps
FprEN 61558-2-9:2008 CLC/SR 96
Safety of transformers, reactors, power supply units and similar products for supply voltages up to 1100 V -- Part 2-9: Particular requirements and tests for class III tungsten filament hand lamps and power supply units incorporating transformers for class III tungsten filament hand lamps

EN 61558-2-12:2001 CLC/SR 96
Safety of power transformers, power supply units and similar devices -- Part 2-12: Particular requirements for constant voltage transformers
FprEN 61558-2-12:2008 CLC/SR 96
Safety of transformers, reactors, power supply units and similar products for supply voltages up to 1100 V -- Part 2-12: Particular requirements and tests for constant voltage transformers and power supply units incorporating constant voltage transformers
EN 61558-2-13:2009 CLC/SR 96
Safety of transformers, reactors, power supply units and similar products for supply voltages up to 1 100 V -- Part 2-13: Particular requirements and tests for auto transformers and power supply units incorporating auto transformers
EN 61558-2-15:2001 CLC/SR 96
Safety of power transformers, power supply units and similar -- Part 2-15: Particular requirements for isolating transformers for the supply of medical locations
EN 61558-2-16:2009 CLC/SR 96
Safety of transformers, reactors, power supply units and similar products for supply voltages up to 1 100 V -- Part 2-16: Particular requirements and tests for switch mode power supply units and transformers for switch mode power supply units
EN 61558-2-17:1997 CLC/SR 96
Safety of power transformers, power supply units and similar -- Part 2-17: Particular requirements for transformers for switch mode power supplies
EN 61558-2-20:2000 CLC/SR 96
Safety of power transformers, power supply units and similar devices -- Part 2-20: Particular requirements for small reactors
FprEN 61558-2-20:2008 CLC/SR 96
Safety of transformers, reactors, power supply units and similar products for supply voltages up to 1100 V -- Part 2-20: Particular requirements and tests for small reactors
EN 61558-2-23:2000 CLC/SR 96
Safety of power transformers, power supply units and similar devices -- Part 2-23: Particular requirements for transformers for construction sites
FprEN 61558-2-23:200X CLC/SR 96
Safety of transformers, reactors, power supply units and similar products for supply voltages up to 1100 V -- Part 2-23: Particular requirements and tests for transformers and power supply units for construction sites
EN 62041:2003 CLC/SR 96
Power transformers, power supply units, reactors and similar products - EMC requirements
FprEN 62041:200X CLC/SR 96
Safety of transformers, reactors, power supply units and similar products for supply voltages up to 1100 V - EMC requirements

The EN 61558-x series deals with safety aspects of power transformers, power supplies, reactors and similar products such as electrical, thermal and mechanical safety

Some examples of small transformers:

- Safety transformers
- Isolating transformers
- Control transformers
- Ignition transformers for gas and oil burners,…

The scope of EN 61558-1 Safety of power transformers, power supplies, reactors and similar products -- Part 1: General requirements and tests are as follow:
Stationary or portable, single-phase or polyphase, air-cooled (natural or forced) separating transformers, auto-transformers, variable transformers, separating transformers, auto transformers, variable transformers and small reactors,

independent or associated, not forming a part of distribution networks and with the following characteristics:

- *rated supply voltage not exceeding 1 000 V a.c.;*
- *rated supply frequency not exceeding 500 Hz;*

Rated output power (and voltages) for the different types of transformers are also specified in the scope of the standard:

Transformer type	**Output Power Single Phase**	**Output Power Poly phase**
Isolating transformers	≤ 25 kVA	≤ 40 kVA
Safety isolating transformers	≤ 10kVA	≤ 16kVA
Separating-/auto-/variable transformers	≤ 1kVA	≤ 5kVA

1.8 Existing legislation and agreements

This section identifies the relevant legislation and agreements for the products within the scope of this study.
It is divided into three parts:

- Legislation and Agreements at European Union level
- Legislation at Member State level
- Third Country Legislation

Please note that MEPS is an acronym for Minimum Energy Performance Standard.

1.8.1 Legislation at European Union level

For the novel reader it is important to know that Europe adopted the so-called 'New Approach' to product regulation and the 'Global Approach' to conformity assessment. Detailed information on this approach can be found in the 'Guide to the implementation of directives based on the New Approach and the Global Approach' (EC, 2000)[16].
The standard elements of the 'New Approach' directives are based on the following principles:

- Harmonization is limited to essential requirements.
- Only products fulfilling the essential requirements may be placed on the market and put into service.
- Harmonized standards, the reference numbers of which have been published in the Official Journal and which have been transposed into national standards, are presumed to conform to the corresponding essential requirements.
- Application of harmonized standards or other technical specifications remains voluntary, and manufacturers are free to choose any technical solution that provides compliance with the essential requirements.
- Manufacturers may choose between different conformity assessments procedures provided for in the applicable directive.

The following European directives might be related to 'transformers' within the scope of this study:

- Directive 89/336/EEC 'Electromagnetic compatibility': Power transformers shall be considered as 'passive elements' in respect to emission of, and immunity to, electromagnetic disturbances and are as such exempted. Note: Certain accessories may be susceptible to electromagnetic interference ! (IEC 60076-1). However the electromagnetic field of the transformer may disturb the performance of electronic equipment situated in the vicinity of the transformer.

[16] http://ec.europa.eu/enterprise/newapproach/legislation/guide/document/1999_1282_en.pdf

Appropriate shielding of the equipment or of the transformer cable boxes may reduce the electromagnetic field. Guidelines for evaluation of the electromagnetic field around power transformers could be found in the technical report TR 50453:2007: "Evaluation of electromagnetic fields around power transformers".

- Directive 2006/95/EC 'Low voltage equipment': For the purposes of this Directive, 'electrical equipment' means any equipment designed for use with a voltage rating of between 50 and 1 000 V for alternating current (and between 75 and 1 500 V for direct current, other than the equipment and phenomena listed in Annex II). This means that power and distribution transformers are exempted. If any of the primary and/or the secondary voltage falls above LVD limits it is not subject to LVD, as understood from Orgalime stakeholders. According to the Danish Energy Authority it sure is when the secondary voltage falls within the LVD limits. Please note that LVD is applicable to independent low-voltage equipment placed on EU market which is also used in distribution transformers and installations, such as control circuits, protection relays, measuring and metering devices, terminal strips, etc. "
  Note: Due to the rated supply voltages ($\leq$ 1000Vac) small transformers must comply with the Low Voltage Directive (2006/95/EC) and thus must carry the CE label
- Directive 98/37/EC on the approximation of the laws of the Member States relating to machinery. The machinery directive is not applicable for transformers as such but may be applicable on certain accessories (e.g. pumps). Stakeholders commented that this is at the edge of the scope of this study.
- Directive 2002/95/EC on Restriction of the use of certain Hazardous Substances in electrical and electronic equipment (RoHS). It is restricted to categories for use with a voltage rating not exceeding 1 000 Volt for alternating current.
- Directive 2002/96/EC on 'Waste Electrical and Electronic Equipment' (WEEE) is not applicable as transformers are not falling under the categories set out in Annex IA.

Please note that Power and distribution transformers do not require a CE mark. However they are subject to the relevant standards and regulations.

Those are related directives but are not intended for products:

- Directive 2004/40/EC on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (electromagnetic fields).This Directive lays down minimum requirements for the protection of workers from risks to their health and safety arising or likely to arise from exposure to electromagnetic fields (0 Hz to 300 GHz) during their work. This can be important for the construction of the transformer station; however it is not relevant for the product on its own.

- Directive 89/106/EEC on the approximation of laws, regulations and administrative provisions of the Member States relating to construction products. There is no measure reported in transformers. Stakeholders commented that this is at the edge of the scope of this study.

- Directive 2006/32/EC is a framework for energy end-use efficiency and energy services. Among other things, this includes an indicative energy savings target for the Member States, obligations on national public authorities as regards energy savings and energy efficient procurement, and measures to promote energy efficiency and energy services. According to Article 14(2) of the Directive, Member States shall submit a National Energy Efficiency Action Plan (NEEAP). NEEAPs shall describe the energy efficiency improvement measures they can include distribution transformer efficiency requirements for local TSOs and NDOs and can be transposed in local legislation.

- Directive 2009/72/EC concerning common rules for the internal market in electricity. Describes in article Article 12 the Tasks of transmission system operators. It is mentioned that each transmission system operator shall be responsible for: ensuring the long-term ability of the system to meet reasonable demands for the transmission of electricity, operating, maintaining and developing under economic conditionssecure, reliable and efficient transmission systems with dueregard to the environment. No further specific guidelines or targets are given related to transformers. Article 25 is similar but for Tasks of distribution system operators.

Those directives are applicable but it is the objective of this study to investigate its application and further implementing measures:

- Directive 2005/32/EC on Eco-design which was also referred as 'EuP Directive' or 'Energy using Products Directive'. This directive establishes a framework for the setting of ecodesign requirements for energy-using products and amending Council Directive 92/42/EEC and Directives 96/57/EC and 2000/55/EC of the European Parliament and of the Council. It should be noted that this study could result in the adoption of a regulation for distribution and/or power transformers.

- Amending Directive 2008/28/EC on Eco-design. This is an amendment on Directive 2005/32/EC related to the implementing powers conferred on the Commission.

- On 21 October 2009, the recast of the Ecodesign Directive 2005/32/EC was adopted (extension to energy related products) by Directive 2009/125/EC on so-called Energy Related Products Directive also referred as 'ERP Directive'.

List of related Ecodesign preparatory studies: see
http://ec.europa.eu/energy/efficiency/ecodesign/working_plan_en.htm
List of related adopted Ecodesign regulation:
http://ec.europa.eu/energy/efficiency/ecodesign/legislation_en.htm
Please note that there are currently no specific requirements on energy efficiency, however this could result from this study within the framework of Directive 2009/125/EC on Eco-design.

1.8.2 Agreements at European Union level

Minimum performance levels or labelling is included in those European standards or agreements:

- EN 60076-1 (IEC 60076-1) series on 'Power transformers. General'(see also section 1.7 for more details);
- EN 50464 series under the general title "Three-phase oil-immersed distribution transformers 50Hz, from 50 kVA to 2500 kVA with highest voltage for equipment not exceeding 36kV" (see also section 1.7 for more details);
- HD 538.1 (superseded by FprEN 50541-1:2009) series under the general title "Three-phase dry-type distribution transformers 50 Hz, from 100 to 2500 kVA, with highest voltage for equipment not exceeding 36 kV" (see also section 1.7 for more details);

1.8.3 Legislation at Member State level

In Spain, National Regulations ask for a minimum level of efficiency for Distribution Transformers (from 50 to 2500 kVA, up to 36 kV) for both, utilities and industrial users based on the lists of losses of EN50464. This is in line with NEEAP in line with the End-use Efficiency & Energy Services Directive 2006/32/EC.

In the Flemish region (Belgium) as well the NEEAP in line with the End-use Efficiency & Energy Services Directive 2006/32/EC (see section 1.8.1) includes distribution transformer efficiency requirements for local TSOs and NDOs. This includes maximum load and no load losses equivalent to List CC' (HD428).

It is expected that many more EU27 countries and/or regions will have specific transformer efficiency requirements in their NEEAP.

In the Flemish region noise levels are part of VLAREM for open space and ARAB for the working environment, they are not linked to transformers as such. Obviously noise levels should be in accordance with the installation requirements for transformers, having these requirements at product level is unneeded because industrial applications could be far more. Similar approaches are applicable in other EU27 countries and/or regions.

In 2000 the Swedish Environmental Management Council introduced distribution transformer requirements for 'Liquid- or gas-filled and dry type transformers within the range of < 1000 MVA' (ref. PSR 2000:6). This method includes a full LCA for 30 years transformer life and a load factor of 50 %. It only requires declaring LCA parameters and does not include load (Pk) and no load losses (Po), hence at this point not in line with the lists of losses of EN50464. The purpose is green procurement and the legal background is unknown

1.8.4 Third Country legislation

Scope:
This section again deals with the subjects as above, but now for legislation and measures in Third Countries (extra-EU) that have been indicated by stakeholders as being relevant for the product group.

IMPORTANT NOTICE ON THE DIFFERENCES IN INTERNATIONAL LINE VOLTAGE STANDARDS:
All European and most African and Asian countries use a supply that is within 10% of 230 V at 50 Hz, whereas Japan, North America and some parts of South America use a voltage between 100 and 127 V at 60 Hz.
Moreover technical standards differ between both groups including the definition on rated power (S), see section 1.7.1.5.
This difference in line voltage and frequency has an influence on the efficiency of the transformer and the sizing of a domestic grid.
In the US and Japan distribution transformer are generally smaller (e.g. 50 kVA) for a smaller group of houses compared to Europe (e.g. 250 kVA). This is because the higher line voltage allows transporting more electricity with the same wire section in Europe.
As a consequence the one-to-one comparison of minimum requirements and benchmarks makes no sense. A comparison is only included hereafter to demonstrate the technical feasibility to have them in place and to show the trends and content.

It should be taken into account that several non European countries are elaborating or have MEPS for transformers (Australia and New Zealand, USA, Canada, etc.) and these

ongoing developments will be followed up. Following is a summary of international initiatives targeting distribution transformers:
There is no such information about power transformers.

USA
The U.S. Department of Energy has published the final rule for the Distribution Transformers Energy Conservation Standard Rulemaking, 72 FR 58190 (October 12, 2007). The Department has determined that energy conservation standards for liquid-immersed and medium-voltage, dry-type distribution transformers will result in significant conservation of energy, are technologically feasible, and are economically justified. This minimum performance efficiency standard (MEPS) came into effect in January 2010 and requires some of the highest mandatory efficiencies in the world. Under a recently settled lawsuit, the DoE must also review the current efficiency standard and perhaps propose an even more efficient standard that would come into effect in 2016.

The tables below show the MAX-TECH LEVELS for liquid-insulated transformers and dry-type transformers. The "Max Tech" level represents the transformer designs that would exist if cost were no object and all design efforts were focused solely on having the highest possible efficiency level. In other words, the max tech levels represent the upper limit of efficiency values considered by the US Department of Energy in the final rule it published in October 2007. The tables below present the max tech values considered by DOE in that final rule:

USA Department of Energy Maximum Technologically Feasible Levels for Single and Three Phase Liquid-immersed Distribution Transformers.
(Tests to be done at 50% of rated loading, 60 Hz operation).

Single-phase		Three-phase	
kVA	Efficiency (%)	kVA	Efficiency (%)
10	99.32	15	99.31
15	99.39	30	99.42
25	99.46	45	99.47
37.5	99.51	75	99.54
50	99.59	112.5	99.58
75	99.59	150	99.61
100	99.62	225	99.65
167	99.66	300	99.67
250	99.70	500	99.71
333	99.72	750	99.66
500	99.75	1000	99.68
667	99.77	1500	99.71
833	99.78	2000	99.73
		2500	99.74

Note: All efficiency values are at 50 percent of nameplate rated load, determined according to the DOE Test-Procedure, 10 CFR Part 431, Subpart K, Appendix A: 71 FR 24972.

USA Department of Energy Maximum Technologically Feasible Levels for Single and Three Phase Dry-Type distribution transformers.
(Tests to be done at 50% of rated loading, 60Hz operation)
[Figures for BIL of 46-95 kV will correspond to rated voltage of about 11 kV.]

Single-phase				Three-phase			
BIL kVA	20–45 kV efficiency (%)	46–95 kV efficiency (%)	≥96 kV (%)	kVA	20–45 kV efficiency (%)	46–95 kV efficiency (%)	≥96 kV efficiency (%)
15	99.05	98.54		15	98.75	98.08	
25	99.17	98.71		30	98.95	98.38	
37.5	99.25	98.84		45	99.05	98.54	
50	99.30	98.92		75	99.17	98.71	
75	99.37	99.02	99.22	112.5	99.25	98.84	
100	99.41	99.09	99.28	150	99.30	98.92	
167	99.48	99.20	99.36	225	99.37	99.02	99.22
250	99.42	99.42	99.42	300	99.41	99.09	99.28
333	99.46	99.46	99.46	500	99.48	99.20	99.36
500	99.51	99.51	99.52	750	99.42	99.42	99.42
667	99.54	99.54	99.55	1000	99.46	99.46	99.46
833	99.57	99.57	99.57	1500	99.51	99.51	99.52
				2000	99.54	99.54	99.55
				2500	99.57	99.57	99.57

Note: BIL means basic impulse insulation level.
Note: All efficiency values are at 50 percent of nameplate rated load, determined according to the DOE Test-Procedure. 10 CFR Part 431, Subpart K, Appendix A; 71 FR 24972.

The US has three tables of efficiency values for distribution transformers. The first two tables below present the MEPS levels that were adopted for liquid-immersed and medium-voltage dry-type transformers by the US Department of Energy in October 2007. The third table presents the MEPS levels that were adopted by the US Congress for low-voltage dry-type transformers as part of the Energy Policy Act of 2005. All of these efficiency levels are presently under review at DOE as part of an active regulatory review programme.

USA Department of Energy Minimum Efficiency Levels for Regulation of Liquid-immersed Distribution Transformers

Single-phase		Three-phase	
kVA	Efficiency (%)	kVA	Efficiency (%)
10	98.62	15	98.36
15	98.76	30	98.62
25	98.91	45	98.76
37.5	99.01	75	98.91
50	99.08	112.5	99.01
75	99.17	150	99.08
100	99.23	225	99.17
167	99.25	300	99.23
250	99.32	500	99.25
333	99.36	750	99.32
500	99.42	1000	99.36
667	99.46	1500	99.42
833	99.49	2000	99.46
		2500	99.49

Note: All efficiency values are at 50 percent of nameplate-rated load, determined according to the DOE Test-Procedure. 10 CFR Part 431, Subpart K, Appendix A

USA Department of Energy Minimum Efficiency Levels for Regulation of Medium-Voltage Dry-type Distribution Transformers at 60 Hz.

kVA	Single Phase Efficiency (%)			kVA	Three Phase Efficiency (%)		
	20–45kV BIL	46–95kV BIL	≥96kV ☐BIL		20–45kV BIL	46–95kV BIL	≥96kV BIL
15	98.10	97.86		15	97.50	97.18	
25	98.33	98.12		30	97.90	97.63	
37.5	98.49	98.30		45	98.☐0	97.86	
50	98.60	98.42		75	98.33	98.12	
75	98.73	98.57	98.53	112.5	98.49	98.30	
100	98.8	98.67	98.63	150	98.60	☐8.42	
167	98.96	98.83	98.80	225	98☐73	98.57	98.53
250	99.07	98.95	98.91	300	98.82	98.67	98.63
333	99.14	99.03	98.99	500	98.96	98.83	98.80
500	99.22	99.12	99.09	750	99.07	98.95	98.91
667	99.27	99.18	99.15	1,000	99.14	99.03	98.99
833	99.31	99.23	99.20	1,500	99.22	99.12	99.09
-				2,000	99.27	99.18	99.15
-				2,500	99.31	99.23	99.20

Note: BIL means basic impulse insulation level. All efficiency values are at 50 percent of nameplate rated load, determined according to the DOE Test-Procedure. 10 CFR Part 431, Subpart K, Appendix A.

USA Department of Energy Minimum Efficiency Levels for Regulation of Low-Voltage Dry-type Distribution Transformers at 60 Hz

Single-phase		Three-phase	
kVA	Efficiency (%)	kVA	Efficiency (%)
10	97.7	15	97.0
15	98.0	30	97.5
25	98.2	45	97.7
37.5	98.3	75	98.0
50	98.5	112.5	98.2
75	98.6	150	98.3
100	98.7	225	98.5
167	98.8	300	98.6
250	98.9	500	98.7
333	97.7	750	98.8
		1000	98.9

Note: All efficiency values are at 35 percent of nameplate-rated load, determined according to the DOE Test-Procedure. 10 CFR Part 431, Subpart K, Appendix A.

It should be noted that the efficiencies listed in the DOE tables are specified for 60 Hz operation. For equivalent 50 Hz operation as used in Australia (and Europe) the corresponding minimum power efficiency levels would be expected to be slightly higher (by less than about 0.1%).

For those who want more detailed information, a full report and the complete regulation can be downloaded in English[17].

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[17] http://www1.eere.energy.gov/buildings/appliance_standards/commercial/distribution_transformers.html

As mentioned before, the US standards and legislation have a lower relevance in this study due to the differences in electrical grid and standards. Material prices are comparable, energy costs are becoming comparable and IEEE and IEC standards are similar.

Canada

Canada uses three Canadian standards for efficiency specifications for distribution and power transformers:

- CSA-C802.1-00, Minimum Efficiency Values for Liquid-Filled Distribution Transformers

This Standard provides minimum efficiency values derived from those defined for liquid-filled distribution transformers in NEMA Standard TP 1. It was found that efficiencies so obtained approximate the results of a survey conducted nationally among Canadian users and manufacturers.

- CSA-C802.2-00, Minimum Efficiency Values for Dry-Type Transformers

This standard apply to single- and three-phase, 60 Hz, dry-type transformers with a primary voltage of 35 kV and below and a secondary voltage of 600 volts and below, rated 15 to 833 kVA for single-phase and 15 to 7500 kVA for three-phase.

The current dry type efficiency levels in Canada differ from the NEMA TP 1 levels because of specific local Canadian manufacturing situations. They are shown in below table.

Canadian Standard Levels for Dry-type Transformers. (from CSA C802.2)

Dry-Type, Single-Phase				Dry-Type, Three-Phase			
kVA	Minimum Low-Voltage, (V)	1.2 kV Class, % eff. at 0.35 of nameplate	BIL 20-150 kV, % eff. at 0.50 of nameplate	kVA	Minimum Low-Voltage, (V)	1.2 kV Class, % eff. at 0.35 nameplate	BIL 20-150 kV, % eff. at 0.50 of nameplate
15	120 / 240	97.70	97.60	15	208Y/120	97.00	96.80
25	120 / 240	98.00	97.90	30	208Y/120	97.50	97.30
37.5	120 / 240	98.20	98.10	45	208Y/120	97.70	97.60
50	120 / 240	98.30	98.20	75	208Y/120	98.00	97.90
75	120 / 240	98.50	98.40	112.5	208Y/120	98.20	98.10
100	120 / 240	98.60	98.50	150	208Y/120	98.30	98.20
167	120 / 240	98.70	98.70	225	208Y/120	98.50	98.40
250	120 / 240	98.80	98.80	300	208Y/120	98.60	98.50
333	120 / 240	98.90	98.90	500	208Y/120	98.70	98.70
500	480	-	99.00	750	208Y/120	98.80	98.80
667	480	-	99.00	1000	208Y/120	98.90	98.90
833	480	-	99.10	1500	480Y/277	-	99.00
-	-	-	-	2000	480Y/277	-	99.00
-	-	-	-	2500	480Y/277	-	99.10
-	-	-	-	3000	600Y/347	-	99.10
-	-	-	-	3750	4160Y/2400	-	99.20
-	-	-	-	5000	4160Y/2400	-	99.20
-	-	-	-	7500	4160Y/2400	-	99.20

- CSA-C802.3-01, Minimum Efficiency Values for Power Transformers.

This Standard applies to power transformers rated from 501 to 10 000 kVA. This Standard specifies maximum losses for power transformers of types similar to or as described in CSA Standard CAN/CSA-C88. The losses specified are for normal designs of transformer, as described in the relevant clauses, but in addition losses are specified for some special designs that are also described.

Canada follows NEMA TP-1 strictly but the mandatory levels apply only for dry type transformers. In Canada the Office of Energy Efficiency (OEE) of Natural Resources Canada (NRCan) has amended Canada's Energy Efficiency Regulations (the Regulations) to require Canadian dealers to comply with minimum energy performance standards for dry-type transformers imported or shipped across provincial borders for sale or lease in Canada. The standards are harmonized with NEMA TP-1 and TP-2 standards.
Amendment 6 of Canada's Energy Efficiency Regulations was published on April 23, 2003. The regulation of dry-type transformers has been included in this amendment with a completion date of January 1, 2005. This requires all dry-type transformers, as defined in this document, manufactured after this date to meet the minimum efficiency performance standards.
As far as oil transformers are concerned, Canada has conducted analysis of MEPS implementation potential and found that the great majority of Canadian oil distribution transformers already comply with NEMA TP-1 so the standard would almost have no influence on the market. The yearly MEPS standard impact would only be 0.98 GWh for

liquid filled transformers compared to saving potential at 132 GWh expected for dry type transformers. Also, Energy Star products are very actively promoted in Canada.

Note: Canada is now changing its standard to be closer to that of the US. In June 2010, NRCan issued a bulletin that presents the efficiency tables, the schedule and the definitions / exclusions. Information on all of these topics can be found electronically at the following link: http://oee.nrcan.gc.ca/regulations/bulletin/drytype-transformers-june-2010.cfm?attr=0

Australia and New Zealand[18]
Australia "recalculated" the American 60 Hz efficiency standard to its 50 Hz frequency and also extrapolated linearly the efficiencies at the size ratings which are different from USA. The Australian program for energy efficiency in distribution transformers, executed by the National Appliance and Equipment Energy Efficiency Committee (NAEEEC), works on two levels

First, there is the Minimum Energy Performance Standard (MEPS), a regulation that bans transformers which do not meet minimum efficiency levels. The MEPS are defined for oil-filled distribution transformers between 10 and 2500 kVA and for dry type distribution transformers between 10 and 2500 kVA, both at 50% load. The MEPS are mandated by legislation, effective 1 October 2004. Under the stimulus of the National Greenhouse Strategy and thanks to the strong will of the parties involved, the creation of the MEPS passed smoothly. The field study to define the scope started in 2000 with the minimum standards written in 2002.
The second track, currently under development, is the creation of further energy efficiency performance standards resulting in a scheme for voluntary 'high efficiency' labelling (see tables below).

Existing and proposed MEPS levels for liquid-immersed transformers

Transformer type	kVA	Power efficiency (%) at 50% load	Proposed New MEPS efficiency level
Single phase (and SWER)	10	98.30	98.42
	16	98.52	98.64
	25	98.70	98.80
	50	98.90	99.00
Three Phase	25	98.28	98.50
	63	98.62	98.82
	100	98.76	99.00
	200	98.94	99.11
	315	99.04	99.19
	500	99.13	99.26
	750	99.21	99.32
	1000	99.27	99.37
	1500	99.35	99.44
	2000	99.39	99.49
	2500	99.40	99.50

18 Technical report "Distribution Transformers: Proposal to increase MEPS Levels" http://www.energyrating.gov.au/library/details200717-meps-transformers.html

Existing and proposed MEPS levels for dry-type transformers

Transformer type	kVA	Power efficiency (%) at 50% load Um = 12 kV		Power efficiency (%) at 50% load Um = 24 kV	
		Existing MEPS	Proposed new MEPS	Existing MEPS	Proposed new MEPS
Single phase (and SWER)	10	97.29	97.53	97.01	97.32
	16	97.60	97.83	97.27	97.55
	25	97.89	98.11	97.53	97.78
	50	97.31	98.50	97.91	98.10
Three Phase	25	97.17	97.42	97.17	97.42
	63	97.78	98.01	97.78	98.01
	100	98.07	98.28	98.07	98.28
	200	98.46	98.64	98.42	98.60
	315	98.67	98.82	98.59	98.74
	500	98.84	98.97	98.74	98.87
	750	98.96	99.08	98.85	98.98
	1000	99.03	99.14	98.92	99.04
	1500	99.12	99.21	99.01	99.12
	2000	99.16	99.24	99.06	99.17
	2500	99.19	99.27	99.09	99.20

New Zealand follows the Australian regulation for distribution transformers.

Japan

Japan has a different type of distribution system, with the last step of voltage transformation much closer to the consumer. The majority of units are pole mounted single phase transformers. The driver for setting up minimum efficiency performance standards was the Kyoto commitment. Transformers, together with other 17 categories of electrical equipment, should meet minimum efficiencies. In case of transformers, the efficiency is defined at 40% load. Target average efficiency has been defined for the year 2006 (oil) or 2007 (dry type), based on the best products on the market in 2003. This Japanese MEPS is currently the most demanding compared to other regulated ones, and is designed in different way than any other ones. The maximum watts of loss (sum of no load and load losses) under the Top Runner programme for different models of transformer are described by equations (see Table 1-8).

Transformer type	# of phases / frequency Hz	Rating	Formula for calculating efficiency	Class
Oil filled	1 / 50 Hz		$E=15,3 * (kVA)^{0,696}$	I
	1 / 60 Hz		$E=14,4 * (kVA)^{0,698}$	II
	3 / 50 Hz	Up to 500 kVA	$E=23,8 * (kVA)^{0,653}$	III-1
		Over 500 kVA	$E=9,84 * (kVA)^{0,842}$	III-2
	3 / 60 Hz	Up to 500 kVA	$E=22,6 * (kVA)^{0,651}$	IV-1
		Over 500 kVA	$E=18,6 * (kVA)^{0,745}$	IV-2
Dry type	1 / 50 Hz		$E=22,9 * (kVA)^{0,647}$	V
	1 / 60 Hz		$E=23,4 * (kVA)^{0,643}$	VI
	3 / 50 Hz	Up to 500 kVA	$E=33,6 * (kVA)^{0,626}$	VII-1
		Over 500 kVA	$E=24,0 * (kVA)^{0,727}$	VII-2
	3 / 60 Hz	Up to 500 kVA	$E=32,0 * (kVA)^{0,641}$	VIII-1
		Over 500 kVA	$E=26,1 * (kVA)^{0,716}$	VIII-2

Table 1-8: Types of distribution transformers in Japan

Please note that the difference between Oil filled and Dry type transformers are related to cooling, see also 1.3.

This scheme is a part of the 'Top runner Program' which either defines the efficiency for various categories of a product type, or uses a formula to calculate minimum efficiency. This program, which covers 18 different categories of appliances, has some major differences compared to other minimum efficiency performance programs. For example, it refers to the average particular manufacturer sold populations while manufacturers or importers who ship less than 100 units in total are excluded, but display obligations must be met regardless of the number of units shipped. The minimum standard is not based on the average efficiency level of products currently available, but on the highest efficiency level achievable. However, the program does not impose this level immediately, but sets a target date by which this efficiency level must be reached. A manufacturer's product range must, on average, meet the requirement. It is not applied to individual products. The program shall deliver approximately 30.3% improvement in efficiency compared to 1999 levels by the target year. Labelling of the products is mandatory. A green label signifies a product that meets the minimum standard, while other products receive an orange label.
Noise level should be determined in accordance with installation environment. Japanese transformers for utility companies are regulated as <45dB in the rural areas, 50dB in other areas.
As mentioned before, the Japan legislation has little relevance in this study due to the differences in electrical grid and standards.

China
In China, the standards have been regularly upgraded starting from 1999. S7 and the next S9 have been replaced with new standard S11, which has losses slightly below Europe's AC' level. The MEPS defines allowable levels for non-load and load losses. These standards, approved by the State Bureau of Quality and Technology Supervision, are defined for distribution and power transformers covered in China. They stipulate maximum load and no-load losses for oil immersed types ranging from 30 to 31500

kVA and for dry types in the range from 30 to 10000 kVA. This regulation has quickly changed the market to higher efficiency units.

A standard for efficiency grades for power transformers is in progress. In the table below some efficiency grades for oil-immersed power transformers are shown.

Energy efficiency grades for 220kV three-phase oil-immersed double-winding load-ratio voltage transformer

Rated capacity kVA		No-load loss kW				Load loss (75℃) kW				Short-circuit impedance %
		Grade 3	T	Grade 2	Grade 1	Grade 3	T	Grade 2	Grade 1	
31500		42.6	37.0	32.3	30.0	151.2	138.5	136.0	134.7	12～14
40000		50.4	43.8	38.2	35.5	175.9	161.1	158.1	156.6	
50000		60.5	52.5	45.8	42.6	211.7	193.9	190.4	188.6	
63000		70.6	61.3	53.5	49.6	246.4	225.8	221.6	219.5	
90000		89.6	77.8	67.9	63.0	322.6	295.5	290.1	287.3	
120000		110.9	96.3	84.0	78.0	387.6	355.0	348.5	345.2	
150000		130.0	112.8	98.4	91.4	453.6	415.6	407.9	404.0	
180000		151.2	131.3	114.5	106.3	524.2	480.2	471.3	466.9	
120000	Low-voltage 66、69kV	114.3	99.2	86.5	80.4	397.6	364.3	357.5	354.2	
150000		134.4	116.7	101.8	94.5	464.8	425.8	417.9	414.0	
180000		156.8	136.1	118.8	110.3	532.0	487.4	478.4	473.8	

The minimum allowable values of no-load loss and load loss of power transformers shall not be higher than Grade 3 levels.
The target ("T") values shall be implemented four years after the day since this Standard is implemented.

India
The Indian Bureau of Energy Efficiency (BEE) has analyzed the feasibility of a distribution transformer minimum efficiency standard. BEE classifies distribution transformers in the range from 16 up to 200 kVA into 5 categories from 1 Star (high loss) to 5 Stars (low loss). 5 Stars represents world-class performance. 3 Stars is being proposed as a minimum efficiency performance standard, and is being widely followed by utilities.

Maximum Permissible Transformer Loss Levels for the Indian BEE Star Classification: for three phase liquid-insulated transformers

The total losses at 50% and 100% loading shall not exceed the values given below:

Rating	1 star		2 star		3 star		4 star		5 star	
kVA	Max Losses at 50% (Watts)	Max Losses at 100% (watts)	Max Losses at 50% (Watts)	Max Losses at 100% (watts)	Max Losses at 50% (Watts)	Max Losses at 100% (watts)	Max Losses at 50% (Watts)	Max Losses at 100% (watts)	Max Losses at 50% (Watts)	Max Losses at 100% (watts)
16	200	555	165	520	150	480	135	440	120	400
25	290	785	235	740	210	695	185	655	160	615
63	490	1415	430	1335	380	1250	330	1170	280	1100
100	700	2020	610	1910	520	1800	440	1700	360	1600
160	1000	2800	880	2550	770	2200	670	1950	570	1700
200	1130	3300	1010	3000	890	2700	780	2400	670	2100

The scheme is a cooperative venture between public and private organizations that issues rules and recommendations under the statutory powers vested with it. The 5-star program stipulates a lower and a higher limit for the total losses in transformers, at 50% load. The scheme recommends replacing transformers with higher star rated units

The 12th of January 2009, the Indian authorities, Bureau of Energy Efficiency (BEE), published the project of regulation before the final adoption in March 2009.
Since this date, the manufacturers will have 6 months to apply the requirements of the labelling. In comparison to the EU energy labelling program, the Indian one was voluntary since this time.
The label shall be displayed on every product and available at the point of sale.
To qualify the star rating, the manufacturers are invited to use the Indian standards such as the IS 1180: 1989 for testing conditions of distribution transformers.

The scope of the regulation for distribution transformer is: oil immersed, naturally air cooled, three phase and double wound non sealed type outdoor distribution transformer of standard ratings of 16, 25, 63, 160, 200 kVA being manufactured and commercially purchased or sold in India.

For labelling criteria, further information is available here:
http://www.bee-india.nic.in/search.php?id=Distribution%20Transformer

Mexico

Mexico sets MEPS at slightly less stringent levels; 0.1% to 0.2% below TP-1 efficiency. As in Australia, the Mexican MEPS includes voluntary and mandatory elements. The Normas Officials Mexicanas (NOM) defines minimum efficiency performance standards for transformers in the range from 5 to 500 kVA, and a compulsory test procedure for determining this performance. For each power category, maximum load and non-load losses are imposed.

The table below shows the Mexican levels that are currently used.

Type	Capacity kVA	Insulation Class		
		Up to 15 kV (%)	Up to 25 kV (%)	Up to 34.5 kV (%)
Liquid-Immersed, Single-Phase	5	97.90	97.80	97.70
	10	98.25	98.15	98.05
	15	98.40	98.3	98.2
	25	98.55	98.45	98.35
	37.5	98.65	98.55	98.45
	50	98.75	98.65	98.55
	75	98.90	98.80	98.70
	100	98.95	98.85	98.75
	167	99.00	98.90	98.8
Liquid-Immersed, Three-Phase	15	97.95	97.85	97.75
	30	98.25	98.15	98.05
	45	98.35	98.25	98.15
	75	98.50	98.40	98.30
	112.5	98.60	98.50	98.40
	150	98.70	98.60	98.5
	225	98.75	98.65	98.55
	300	98.80	98.70	98.60
	500	98.90	98.80	98.7

Note: These efficiency levels are applicable at 100 percent of nameplate load.

Note that the power efficiency levels are those determined at 100% of nameplate rating. These will be slightly less than at 50% for the same transformer. Only liquid-filled transformers are regulated. Dry-type transformers are in use but are not included in the mandatory scheme.

1.9 General conclusions on standards and legislation

In Europe, but also internationally (USA, Canada, Australia,..) there has been a substantial level of activity concerning new efficiency standards for (distribution) transformers. Several levels of efficiency classes are defined within EN and international standards, for example the AA' class (EN 50464-1), "3 star" (Indian BEE star classification), "Top Runner" (Japan)…

Comparison of these international efficiency classes is not always obvious because of:

- differences in electricity distribution systems: grid voltages, grid frequencies (50 Hz versus 60Hz),…
- differences in definitions for apparent power of the transformer (input power versus output power)
- differences in load levels at which the efficiency of the transformer is measured (50% load, 100% load,…)

The European industry currently uses a standard (EN 50464) for oil-filled distribution transformers and harmonized document (HD 538 – superseded by EN 50541-1:2009 in 2010) for dry-type distribution transformers that includes MEPS. This is not included in legislation so far and is used for procurement specifications only.
A comparison of the different MEPS with EN-50464 is included in Figure 1-9, the efficiency is calculated at 50 % load (source: Hitachi). Please note also the difference between 50 and 60 Hz transformers. In Japan and USA also smaller distribution transformers are used, as illustrated.

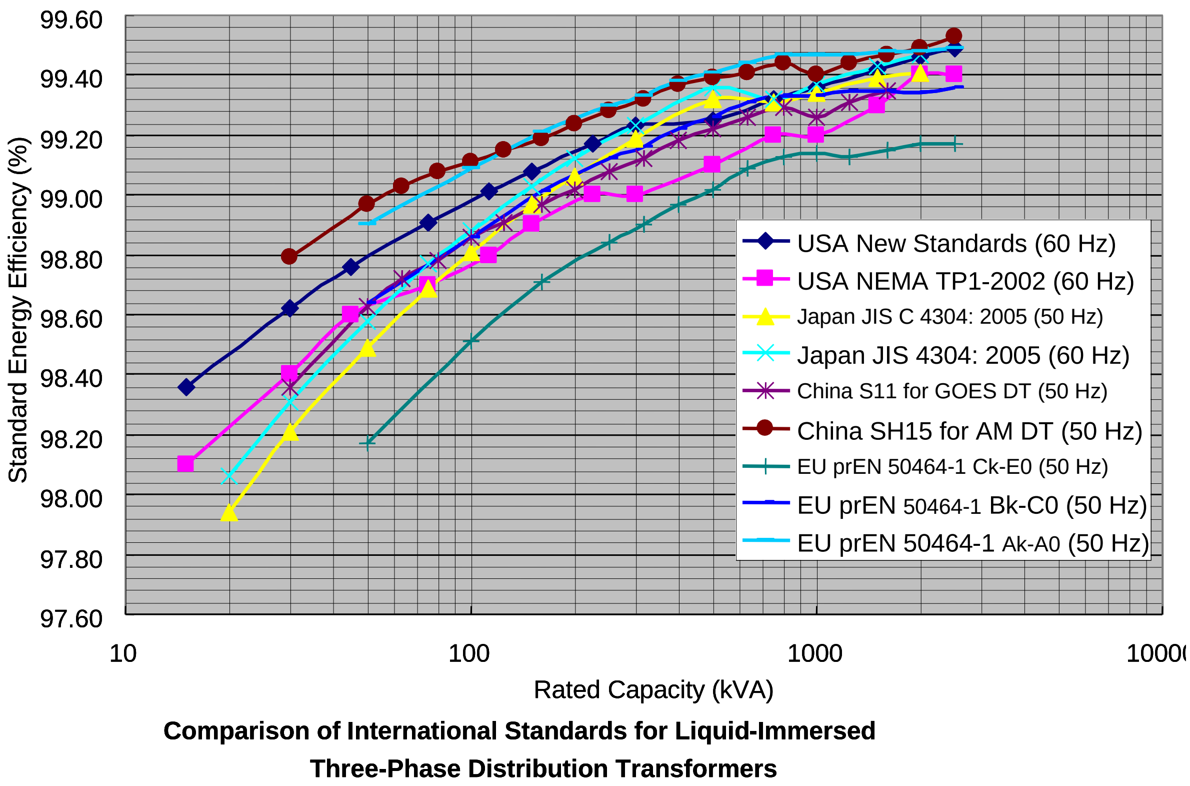

Figure 1-9: Comparison of international transformer standards (Source: Hitachi (2009))

Notes on this comparison:

- This comparison should be handled by care because the definition of rated power (kVA) differs in IEC standards compared to IEEE.
- Moreover, the line frequency and voltage differs in EU compared to US(JP) and this can have an impact on transformer design and efficiency. See notice in the beginning of this section.
- Some MEPS are in efficiency at 50 % load factor, in task 3 it will be shown that it is representative for industry transformers but not for the distribution transformers (20 % load factor). The EN 50464 is more detailed and specifies load (Pk) and no load (Po) losses.
- Only in China there are MEPS proposed for power transformers up to 180 MVA (not included in the graph)
- It is not the purpose to start analyzing the performance of transformers here, this will be done in more detail in later Chapters.

Conclusions on Power and distribution transformers (T&D sector):

So far there are no missing test standards or measurement procedures on energy use for T&D transformers identified in this study. There are also no gaps nor missing standards on other ecodesign parameters reported by the stakeholders.

For distribution and industrial transformers there are minimum performance levels for load and no load losses defined in standards EN50464-1, HD 538.1 or FprEN50541-1. A final recommendation on raising the existing minimum energy performance level is a topic of Task 7 on policy recommendations after the full analysis in the subsequent tasks. Also, the highest performance level (Ak, A0) defined herein does not mean that significant lower losses can't be achieved with actual technology. This will also be evaluated in subsequent tasks.

The maximum allowable tolerance on the total losses (sum of the load and no-load losses) is + 10% of the total losses (IEC 60076-1). This could be reduced to a lower value (+ 7.5 % or even lower) as suggested during the second stakeholder meeting.

The values of the losses or the efficiency class of the transformer is not a mandatory information on the rating plate of the transformer (IEC 60076-1/ 7.1). It is appropriate to take these values into the list of mandatory information on the rating plate of the transformer.

There are no MEPS defined for Power transformers (>5000 kVA). A similar approach as used for oil filled distribution transformers (EN 50464-1) could be considered. Only China has a draft proposal for MEPS for load and no load losses. Currently European TSOs have already their own public tender specifications that take load and no-load losses into account when assessing the Total Cost of Ownership (TCO), more details on this approach are also in chapters 2 and 3. A final recommendation is a topic of Task 7 on policy recommendations after the full analysis in the subsequent tasks.

Note the fire behaviour is only included in the standard on dry type transformers in IEC 60076-11. The behaviour of silicon transformer under fire had never been tested under standardisation condition and pressure in the tank could lead to special results. Therefore on update of the IEC 60076-11 standard for oil filled transformers might be needed taking new developments and test results into account. This will be further discussed in task 5.

Conclusions on small industrial transformers:

For smaller industrial transformers there is no formal standard to measure the load and no load losses. However they use in practice a similar method as distribution transformers (EN 60076-x series). This gap should be closed as soon as possible..

There are no MEPS reported for these small industrial transformers. Therefore MEPS will be considered in Task 7 on policy recommendations and can only be done after the full analysis in the subsequent tasks.

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		EN-Standards												
Study scope All	Major subcatogory name	Efficiency Performance	Test & Measurement	LwA dB (A): Sound power level	EMF (Electro Magnetic Field)	Hazardous substances - PCB	Short-circuit impedance	Rated Voltage of the high-voltage winding (Vrms)	Rated Voltage of the low-voltage winding (Vrms)	Insulation temperature class	Protection class (IP)	Fire behaviour class	Environmental class	Climate class
y	**MV/LV Distribution oil transformer**	EN 50464-1[8]	EN 60076-x	EN 60076-10	EN 50413[3]	EN 60296[7]	EN 60076-1	EN 60076-1	EN 60076-1	NA[4]	EN 60529	NA[4]	NA[4]	NA[4]
y	**MV/LV Distribution dry transformer**	HD 538[1]	EN 60076-x	EN 60076-10	EN 50413[3]	NA[4]	EN 60076-11[5]	EN 60076-11[5]	EN 60076-11[5]	EN 60085[5]	EN 60529	EN 60076-11[5]	EN 60076-11[5]	EN 60076-11[5]
y	**Line voltage restorers (dry)**	None	EN 60076-x	EN 60076-10	EN 50413[3]	NA[4]	EN 60076-1	EN 60076-1	EN 60076-1	EN 60085[5]	EN 60529	EN 60076-11[5]	EN 60076-11[5]	EN 60076-11[5]
y	**DER LV/MV transformers (oil-dry/20-80)**	see distri.	EN 60076-16[2]	EN 60076-10	EN 50413[3]	EN 60296[7]	EN 60076-1	EN 60076-1	EN 60076-1	EN 60085[5]	EN 60529	EN 60076-11[5]	EN 60076-11[5]	EN 60076-11[5]
y	**Industry MV/LV oil transformer[6]**	EN 50464-1	EN 60076-x	EN 60076-10	EN 50413[3]	EN 60296[7]	EN 60076-1	EN 60076-1	EN 60076-1	NA[4]	EN 60529	NA[4]	NA[4]	NA[4]
y	**Industry MV/LV dry transformer[6]**	HD 538[1]	EN 60076-x	EN 60076-10	EN 50413[3]	NA[4]	EN 60076-1	EN 60076-1	EN 60076-1	EN 60085[5]	EN 60529	EN 60076-11[5]	EN 60076-11[5]	EN 60076-11[5]
y	**Power transfomer (oil)**	None	EN 60076-x	EN 60076-10	EN 50413[3]	EN 60296[7]	EN 60076-1	EN 60076-1	EN 60076-1	NA[4]	EN 60529	NA[4]	NA[4]	NA[4]
y	**Phase Change transformer (oil)**	None	EN 60076-x	EN 60076-10	EN 50413[3]	EN 60296[7]	EN 60076-1	EN 60076-1	EN 60076-1	NA[4]	EN 60529	NA[4]	NA[4]	NA[4]
y	**Small industrial transformers (dry)**	None	EN 61558-1	None	EN 62041	NA[4]	EN 61558-x	EN-61558-x	EN-61558-x	EN 60085[5]	EN 60529	EN-61558-x	EN-61558-x	

1 Will be superseded by EN-50541-1
2 Transformers for wind turbine applications - Standard in Draft stage
3 Basic standard on measurement and calculation procedures for human exposure to electric, magnetic and electromagnetic fields (0Hz-300GHz)
4 Not applicable
5 Applicable for dry type transformers and update might be needed
6 Same technology as distribution tranformers
7 EN 60296: Mineral oil, EN 60836: Dimethyl silicone, EN 61099: Synthetic ester, EN 60867: Synthetic Hydrocarbon
8 EN 50464: Level A0 or Ak might not be ambitious enough

Figure 1-10: Summary of EN Transformer Standards

CHAPTER 2 ECONOMIC AND MARKET ANALYSIS

Scope:

In this chapter, the market and stock data for the following time periods are identified:

- 1990 (Kyoto reference);
- 2004-2007 (most recent real data);
- 2020-2025 (forecast, year in which all new eco-designs of today will be absorbed by the market).

This chapter includes insights into the latest market trends to indicate the place of possible eco-design measures in the context of the market structures, and ongoing trends in product design (see §2.3). Additionally, §2.4 provides information on user expenditure data, e.g. transformer prices and electricity prices, which will be used to calculate the life-cycle-cost of the transformers.

It is not the purpose of chapter 2 to forecast the effect of future policy options related to transformers. Future policy options and their estimated impacts are discussed in chapter 7.

According to the MEEuP methodology, *'primary MEEuP market parameters'* that will be used for environmental and economical impact modelling in chapters 4, 6 and 7 are identified. These parameters reflect the following '*generic economic data'* (see §2.1*)*:

- Installed transformers (stock) according to the product categories defined in section 1.1 most recently (2004-2007), and in the past (1990 estimation) per EU-27 country (§2.2.2 and §2.2.2.2);
- Annual transformer sales (market) according to the product categories defined in section 1.1 per EU-27 country (§2.2.3);
- Annual transformer sales can be subdivided into 'transformer replacement sales' and 'new installed transformer sales'. The number of annual transformer replacement sales is assumed equal to the 'Installed transformer stock' over 'Average product life'. This approach is mainly useful for analysing market trends.
- Transformer sales growth (% or physical units) according to the product categories defined in section 1.1 to forecasting the impact in Business as Usual (BAU) for 2012 and 2020 for a BAU scenario (§2.2.3.2);
- Average Product Life (in years) (§2.2.6.1);

Some *additional market model parameters* are defined. These parameters are used to correct or double check Eurostat or other available market data and to assist in predicting 2020 growth rates for the scenarios and assessment of the impact of introducing more energy efficient transformers in Europe (§0).
The idea is that distribution transformers are linked to the population and installed residential and non residential (tertiary sector, industry, etc.) electricity park. Also the

market share of Renewable Energy Systems (RES) in the total electricity consumption will be assessed. Because RES is generally more geographically distributed and on a smaller scale than traditional electricity generation methods (coal, gas, nuclear, hydro), this may be an important driver in stock growth.

Furthermore the average load and no-load losses on the stock and sales, and the current average efficiency of the installed transformer park is indicated.
In the BAU scenario, the average transformer efficacy is kept constant. This might of course underestimate the losses of the past and overestimate the losses of the future. A sensitivity analysis at the end of the study could check these boundaries.

Summary:

The results are summarised in Table 2-1.

For the total figure industry and power distribution transformers there should be no doubt that the eligibility criterion (Art. 15, par. 2, sub a, of the Energy-related-Products Directive 2009/125/EC) is met as annual sales, in the EU market, are above 200 000 units. Moreover, this is certainly the case when the 'unit' is defined as the 'functional unit' used within this study being 1 kVA (see Chapter 1 for definition). Distribution transformers represent the largest share of both the stock and sales. More details about the market size are given in the table below and typical losses are included in the Task report. T&D transformers are mainly produced by large enterprises while smaller industrial transformers often by SMEs. Transformer prices are strongly influenced by commodity prices.

The main European industry players for the distribution and power transformers are big international groups like ABB, Siemens, Areva, Schneider Electric, and some large/medium size companies like Cotradis, Efacec, Pauwels, SGB/Smit and Transfix. Transformer manufacturers from outside the EU include GE, Hitachi (Japan) and Vijai (India). T&D Europe is the representative of the European Transformer Manufacturers, regrouping the Austrian, Belgian, British, French, German, Italian, Spanish, Portuguese and the Netherlands's National Associations. Smaller industrial transformers are mainly produced by European SMEs. It is a niche market and clients often directly order with the manufacturer. It is estimated that there should be about 50 SMEs active in production; often these companies have only a few employees.

There is little maintenance schedules for transformers (annual checks for dust build-up, vermin infestation, and accident or lightning damage) and it can be assumed that these repair and maintenance costs will not change with increased efficiency.

Transformer type	Rated Power S in *KVA*		Class		Stock	Stock	Stock	New installed sales		Replacement sales	Total sales		Total sales		
					1990	2005	2020	1990 -2005	2005 - 2020		1990 - 2005	2005 - 2020	1990	2005	2020
	stock	*sales*	*stock*	*sales*	*1000 units*	*1000 units*	*1000 units*	*% p.a.*	*% p.a.*	*% p.a.*	*% p.a.*	*% p.a.*	*Units p.a.*	*Units p.a.*	*units p.a.*
Smaller Industrial Transformers	16	16	Pk 750 W P0 110 W	Pk 750 W P0 110 W	750	750	750	0	0	10	10	10	75000	75000	75000
Distribution transformer (oil)	250	400	EoCk	DoCk	2714	3600	4459	1.9	1.4	2.5	4.4	3.9	119438	140400	173.891
DER transformers oil immersed	2000	2000	EoCk	EoCk	0.25	20	89	34	10.5	0	34	10.5	94	2.900	12967
DER transformers dry-type	2000	2000	Equivalent to oil	Equivalent to oil											
Industry oil transformer	630	1000	EoCk	EoCk	603	800	991	1.9	1.4	4	5.9	5.4	35590	43200	53505
Industry dry transformer	800	1250	Pk 10000 W Po 2500 W	Pk 13100 W Po 2800 W	128	170	211	1.9	1.4	3.3	5.2	4.7	6708	8047	9966
Power transformer	100000	100000	Pk 300000 W Po 80000 W (anno 1990)	Pk 326000 W Po 40500 W	49	64.35	80	1.9	1.4	1.4	3.3	2.8	2539	3046	3772
Phase	100000	100000	Pk 300000 W Po 80000 W	Pk 326000 W Po 40500 W	0.49	0.65	0.81	1.9	1.4	1.4	3.3	2.8	26	31	38
Total transformers					3466	4655	5832						239396	272623	329140

Table 2-1: Summary of MEEuP market parameters

2.1 Generic economic data

2.1.1 Definition of 'Generic economic data' and data sourcing

“Generic economic data” gives an overview of production and trade data as reported in the official EU statistics. It places the transformers within the total of EU industry and trade.

To investigate the general transformer market, Europroms[19]-Prodcom statistics are screened, and verified with recent data from stakeholders (viz. meetings T&D Europe 2009).

Although the aim is to take into account the specific attributes of the Member States’ national markets, much of the analysis can only be performed at the level of the EU-27 market, as data is mostly available in aggregated form.

2.1.2 Generic economic data from the Europroms-Prodcom statistics

Within the Europroms-Prodcom statistics, the transformer market is divided on the basis of power rating and type of transformer, i.e. liquid or non-liquid (dry) dielectric transformer. This classification of the market analysis is different from the classification as defined under the scope of this study (see chapter 1 § 1.4.7). A link between the Prodcom classification and the scope of this study is made in the Table 2-2.

Prodcom Code	Prodcom Description	Prodcom Simplified Name	Link with scope of report
31.10.41.30	Liquid dielectric transformers having a power handling capacity ≤ 650 kVA	LLP (liquid low power)	Distribution transformer (oil)
31.10.41.53	Liquid dielectric transformers having a power handling capacity > 650 kVA but ≤ 1 600 kVA	LMLP (liquid medium low power)	Industry and DER transformers oil immersed
31.10.41.55	Liquid dielectric transformers having a power handling capacity > 1 600 kVA but ≤ 10 000 kVA	LMHP (liquid medium high power)	
31.10.41.70	Liquid dielectric transformers having a power handling capacity > 10 000 kVA	LHP (liquid high power)	Power transformers and phase transformers
31.10.43.30	Transformers, nes[20], 16 kVA < power handling capacity < 500 kVA	DLP (dry low power)	Industry dry transformer
31.10.43.50	Transformers, nes, power handling capacity > 500 kVA	DHP (dry high power)	DER and industry dry transformers

Table 2-2: Transformer market classification by Prodcom and scope of this report

2.1.2.1 Prodcom Market Data

The Europroms-Prodcom statistics contains data on the production, imports, and exports in terms of both quantity of units and monetary value. For various reasons[21],

[19] Europroms is the name given to published Prodcom data. It differs from Prodcom in that it combines production data from Prodcom with import and export data from the Foreign Trade database.
[20] ‘nes’ means ‘not elsewhere specified’
[21] The general advantages, flaws and limitations of these official EU statistics are extensively

these data must be considered only as approximations. All the required data for transformers is summarised by apparent consumption[22] = Production + Imports – Exports

The market data in quantity of units and monetary value (see Table 2-3) was obtained for the relevant product categories from Eurostat[23] for the EU-27[24] for the years 1995[25] and 2004 – 2007.

discussed in i) the MEEUP Methodology Report and ii) the Eurostat data shop Handbook (part 6.4.2.) Europroms-Prodcom data, version 29/08/2003.

[22] "Apparent consumption" is the estimation of the yearly consumption for each product based on the amount produced plus the amount imported minus the amount exported. This is the rationale for combining Prodcom and Foreign Trade data in Europroms (Eurostat Data Shop Handbook, part 6.4.2 Europroms-Prodcom data, version 29/08/2003).

[23] http://epp.eurostat.ec.europa.eu (Theme "Industry, trade and services", last consulted 19/02/2009)

[24] In this study the interest is trade leaving and entering the EU-27. Despite the fact that Eurostat has data for each EU Member State, these data cannot be used as it counts trade between Member States. Therefore, only industry data on an EU-27 level was used.

[25] Data for the EU-27 was estimated by determining the relation between EU-15 and EU-27 data for the years 2004 and 2005, averaging this ratio for the two years, and then applying this to the EU-15 in 1995.

Product Group Prodcom / scope study	Year	Production (1000 units)	Production (million €)	Import (1000 units)	Import (million €)	Export (1000 units)	Export (million €)	Apparent Consumption (1000 units)	Apparent Consumption (million €)
31.10.41.30 LLP / Distribution oil	1995*	525.85	418.11	270.77	14.91	175.21	68.71	621.40	364.31
	2004	208.45	372.55	1096.39	34.38	115.30	72.91	1189.54	334.02
	2005	207.69	436.97	541.48	35.47	53.26	79.13	695.91	393.31
	2006	223.79	631.08	1082.33	54.24	101.98	90.62	1204.14	594.70
	2007	230.89	796.94	1030.21	75.47	221.62	111.38	1039.48	761.02
31.10.41.53 LMLP / Industry and DER oil	1995*	19.08	156.13	21.46	4.09	21.54	26.98	19.00	133.24
	2004	19.72	182.97	8.11	20.44	6.08	27.01	21.75	176.41
	2005	20.92	191.82	9.29	21.64	14.29	30.66	15.92	182.80
	2006	26.55	292.96	47.82	24.53	17.16	37.37	57.21	280.11
	2007	29.57	369.64	79.26	22.76	44.51	40.36	64.33	352.05
31.10.41.55 LMHP / Industry and DER oil	1995*	3.39	138.82	3.12	4.89	22.51	36.92	-16.00	106.79
	2004	4.54	213.02	823.24	32.52	8.77	45.32	819.01	200.22
	2005	3.95	181.17	1222.44	23.95	12.08	39.07	1214.32	166.05
	2006	5.39	231.24	1468.17	41.45	10.23	68.99	1463.32	203.70
	2007	6.77	328.21	1423.65	50.64	25.30	72.09	1405.13	306.76
31.10.41.70 HP / Power oil	1995*	2.24	865.46	18.01	27.23	56.18	352.78	-35.93	539.92
	2004	2.98	1009.22	63.11	36.57	212.56	427.36	-146.47	618.43
	2005	3.38	1229.41	430.04	46.36	2.51	540.35	430.90	735.42
	2006	3.79	1457.22	7.29	48.68	4.45	580.10	6.63	925.81
	2007	4.64	2007.58	32.04	68.07	41.07	642.33	-4.39	1433.32
31.10.43.30 DLP / Industry dry	1995*	5565.53	161.20	3289.82	25.34	864.06	83.09	7991.29	103.45
	2004	307.55	216.90	3370.72	41.20	374.26	88.41	3304.01	169.69
	2005	272.35	220.13	4071.17	31.74	411.41	79.59	3932.11	172.28
	2006	899.84	800.00	3317.19	56.46	389.52	106.10	3827.50	750.36
	2007	395.99	397.18	6151.42	71.81	690.73	139.67	5856.69	329.32
31.10.43.50 DHP / DER and industry dry	1995*	28.35	350.65	1255.07	17.46	22.43	84.71	1260.99	283.39
	2004	77.43	474.45	210.68	24.69	56.01	130.48	232.10	368.66
	2005	93.51	538.51	198.06	39.84	123.05	141.98	168.52	436.37
	2006	84.06	766.20	447.77	68.26	210.35	252.08	321.48	582.38
	2007	123.75	804.64	848.29	72.23	194.00	335.81	778.04	541.06

Negative apparent consumption (not valid): due to inconsistencies between the quantity and value of imports and exports

Table 2-3: Transformer market data within the EU-27, Prodcom data

The market trends for different categories of transformers are presented in Figure 2-1 (in units) and Figure 2-2 (in Euros).

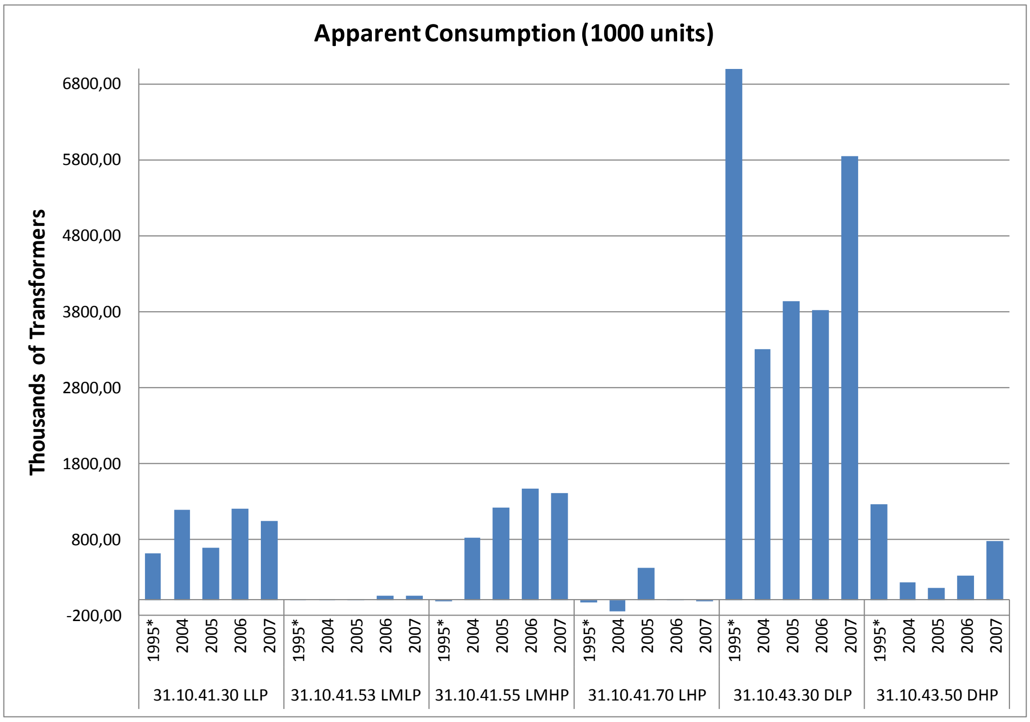

Figure 2-1: Transformer market for the EU-27, in thousands of units

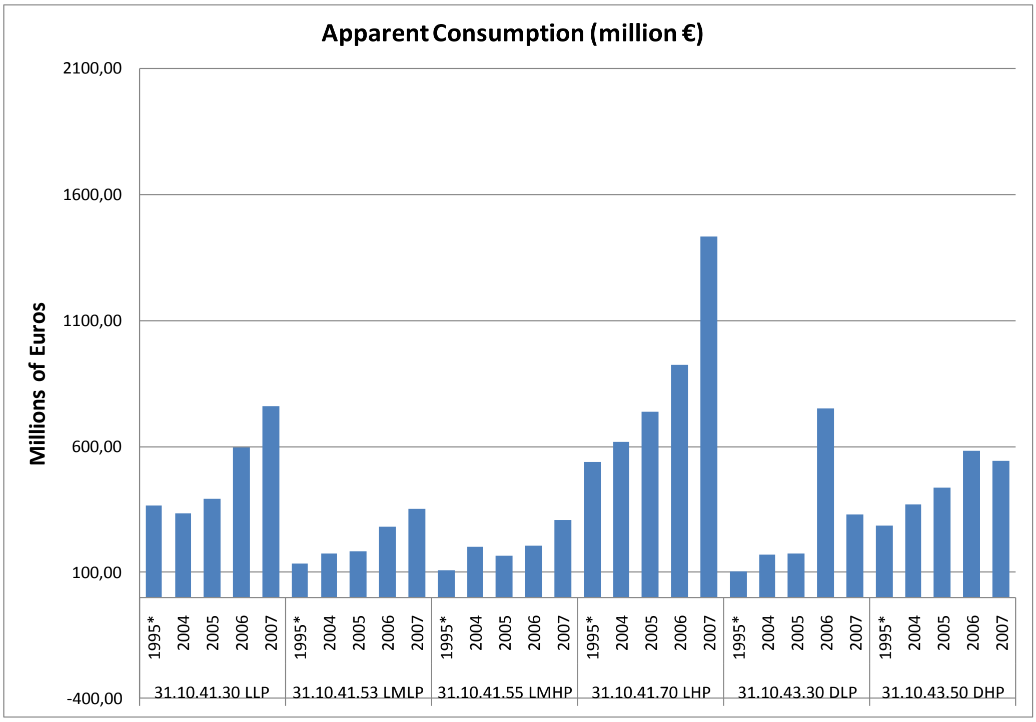

Figure 2-2: Transformer market for the EU-27, in millions of Euros

The market data from Prodcom shows that:

- The low voltage dry industry transformer (DLP) is by far the largest market segment with an apparent consumption of over 5.8 million units in 2007 and represents about 64% of the market. This is over 4 million units and a 49% greater market share than the next largest category, the medium voltage oil immersed industry transformers (LMHP). Apparent consumption of the low voltage dry industry transformer (DLP) has also been generally increasing between 2004 and 2007, with an overall increase of 77%.

- The low voltage oil immersed industry transformer (LMLP) and the power transformer (LHP) are negligible in terms of market size, representing less than 1% of apparent consumption in 2007.

- Imports of transformers far outweigh EU-27 production. For the years 2004 – 2007, imports exceed production by an average of 6.18 million units and a ratio of 9.23 import to production units.

  However, this is not confirmed in terms of monetary value. The value of production over the 2004-2007 period is €3.28 billion greater than import value, which is a produced to imported ratio of 13.6. This huge difference in monetary value between the produced and imported units can impossibly be explained by price differences between EU and non-EU as this would mean that the value of an imported unit is less than 2% of a unit produced in the EU-27. This inconsistency between unit figures and monetary value, i.e. where more units are imported but much greater value is produced, is most likely due to unreliable data from Prodcom.

  The category with the largest market share, low voltage dry industry transformers, imported on average 3.76 million more units than it produced each year between 2004 and 2007. In monetary terms, an average of €358 million more value was produced than imported during the same period.

  The second largest market category, medium voltage oil immersed industry transformers, imported an average of 1.23 million units each year between 2004 and 2007. Over the same period, an average €201 million more were produced than imported.

  The distribution oil immersed transformers (LLP), the third largest market group, imported an average of 0.72 million more units than produced each year from 2004 to 2007. On the contrary, each year, an average €509 million more were produced than imported.

- The EU-27 is not a net-exporter of any type of transformer.

Important note:

The Eurostat numbers for '31.10.43.30-Transformers, nes , 16 kVA < power handling capacity < 500 kVA'. This category of transformers includes the smaller industrial transformers discussed in chapter 1 and other transformers such as e.g. measurement transformers (current/voltage), welding transformers, and plasma power supplies (X-ray, ..).

Eurostat might also include bookkeeping errors, especially for small sales volumes categories when they are confused with large sales categories(e.g. A 20 VA transformer might be confused with 20 kVA).

2.1.2.2 Prodcom Sales growth

Because the data from 1995 is only an estimate, it is more reasonable to assess trends between 2004 and 2007. However, it is important to remember that the growth of apparent consumption in units is not linear from 2004 to 2007, as seen in Figure 2-1. Apparent consumption is used to summarize the results in graphical form in Figure 2-3 to Figure 2-5, Figure 2-3 shows absolute change, while Figure 2-4 and Figure 2-5 display relative change both in units and in Euros, which is the contribution of each category of transformer to the overall growth of the market. It is interesting to note that quantity of units and the market value do not appear to be directly related, e.g. negative unit growth but positive monetary growth with LLP (distribution oil) and LHP (power oil) transformers. This could be related to changes in material prices or supply and demand changes (i.e. sudden increase in demand for this kind of transformers due to higher power production and demand, combined with limited transformer production capacity lead to higher price settings), or to the unreliability of the Prodcom data as already mentioned above.

- In terms of absolute growth of apparent consumption in units, DHP (DER and industry dry) is leading with 235%, followed by LMLP (Industry oil (LV)) with 196%. However, for relative growth, DLP (industry dry) is strongest by contributing to 68% of the growth in the transformer market.
- For absolute growth of the monetary value of apparent consumption, LHP (power oil) and LLP (distribution oil) are leading with 132% and 128% growth, respectively. These are also the two strongest contributors to relative growth, with LHP (power oil) having 44% growth and LLP (distribution oil) 23%.

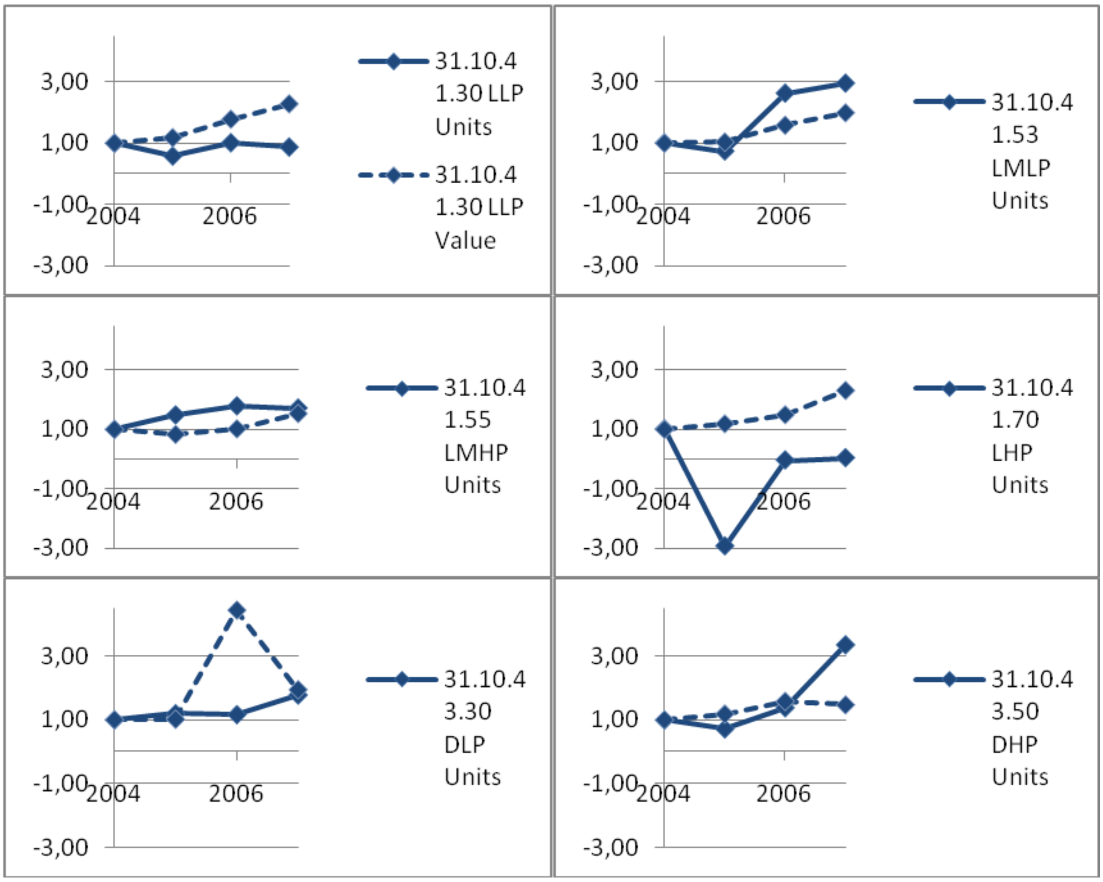

Figure 2-3: % Change of Apparent Consumption from 2004 – 2007

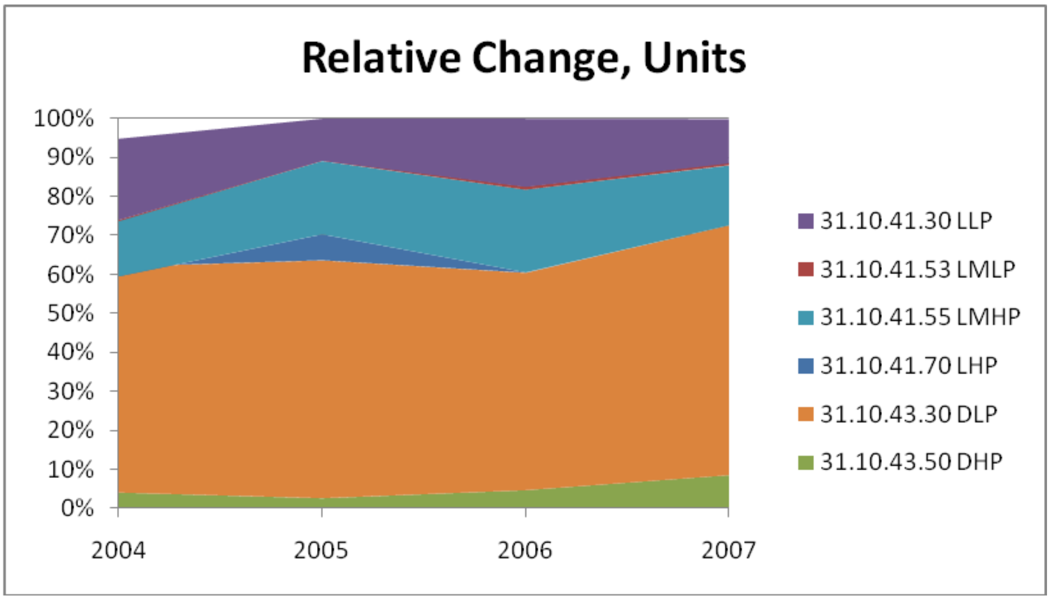

Figure 2-4: % Relative Change of Apparent Consumption (in value) from 2004 – 2007

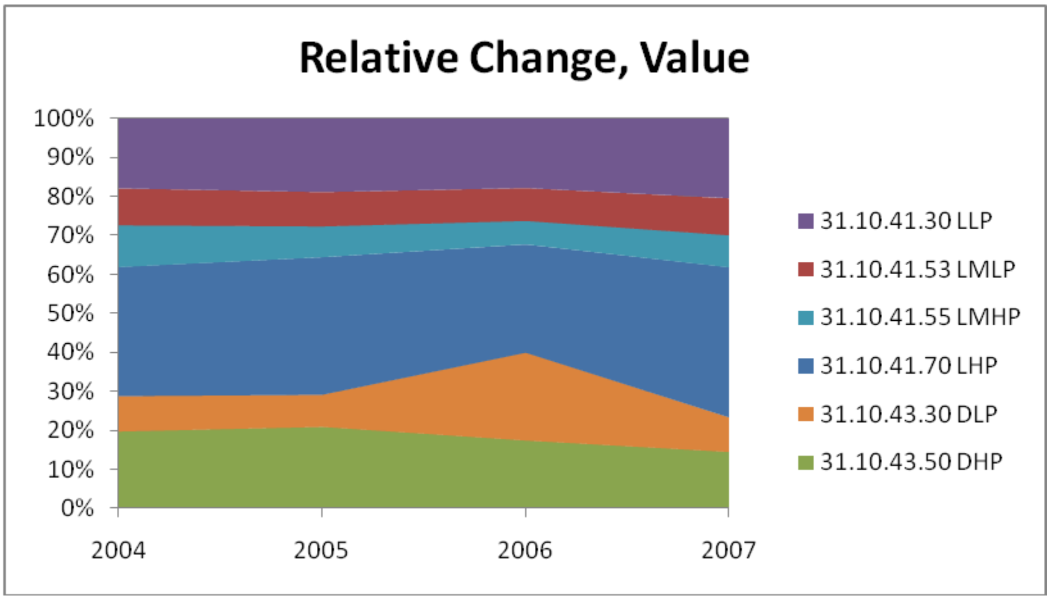

Figure 2-5: % Relative Change of Apparent Consumption (in units) from 2004 – 2007

The average price for each Prodcom category cannot be calculated based on Eurostat data due to the inconsistencies within the data. In one case, the calculation based on Eurostat data results in a negative price per transformer.

2.1.3 Generic economic data from EU transformer T&D industry associations

In order to verify the Europroms-prodcom data, an overview of the number of units installed on EU level and the recent sales figures are provided by the sector organization (T&D Europe, May 2009).

Table 2-4 presents the number of distribution, large industry and power transformers installed in Europe together with the prediction of the sales figures for 2009.

	Total EU27
Distribution and industry distribution (dry-type and oil immersed)	
Total installed	5 040 000
Sales figures 2009	248 600
Power transformers and phase transformers	
Total installed	65 500
Sales figures 2009	1 310

Table 2-4: Overview of the total number of transformers installed in 2009 and expected sales figures for 2009(T&D Europe, May 2009)

These figures show that anno 2009 about 5000000 distribution transformers and 65500 power transformers were installed.

Compared to the Prodcom data the number of installed transformers could be much higher. The Prodcom data shows that the apparent consumption till 2007 in units of distribution and industry transformers is over 10 million units and for power transformers 250 000 units. It is not assumable that a lot of these transformers were replaced over this 12 year period as most transformers were sold after 2004. Prodcom data therefore seems to indicate that more than 2 to 3 times more transformers are installed in the EU-27. However, as mentioned before, the Europroms-prodcom data shows some inconsistencies and could include errors and is not considered to be a reliable source.

2.1.4 Generic economic data: conclusion

The EU statistics and figures from the EU transformer industry (T&D Europe), show that the production/sales figures for distribution, industry and power transformers comply with the eligibility criterion from the Ecodesign Directive, viz. more than 200000 units sold per year and smaller industrial transformer sales was estimated at about 75000 units per year.
Eurostat data shows inconsistencies, input data for the MEEuP Model is retrieved from market data from one sector organisations (see above) and other information sources 2.2.1. These are further elaborated in paragraph 2.2. At the end a sensitivity analysis will be required to verify the impact of these input data, e.g. effect if number of installed units is much lower or higher than 5000000 units.
As a consequence, for the total figure of distribution and power transformers there should be no doubt that the eligibility criterion (Art. 15, par. 2, sub a, of the Energy-related-Products Directive 2009/125/EC) is met as annual sales is well above 200000 units. Moreover, this is certainly the case when the 'unit' is defined as the 'functional unit' used within this study being 1 kVA (see Chapter 1 for definition).

2.2 Market and stock data

Scope:
To estimate the past, current and future EU-wide environmental impact of transformers the EU market and stock data needs to be identified. As the Europroms-prodcom statistics show some inconsistencies, it is not considered to be reliable. Therefore alternative sources are investigated in this section. The main figures to be retrieved are:

number of units installed for each category defined under § 1.4.7 in 1990, 2004 and 2020;

recent sales (new and replacement) and sales growth.

2.2.1 Market and stock data sources

Due to the inconsistencies and unreliability of the Eurostat data in section 2.1.2, the following approaches for retrieving market data, were explored:

- Data from EU R&D project data:

  Various studies have been conducted on the energy use of distribution transformers for EU R&D programmes (IEE-reports):

  - The most recent overview was given in the SEEDT-study related to the analysis of existing situation of energy efficient transformers, SEEDT, 2005.
  - For the additional market parameters the reports on the following studies are used as main sources:

- ▪ 'Electricity Consumption and Efficiency Trends in the Enlarged European Union - Status report 2006', JRC, 2007.
- ▪ 'The scope for energy saving in the EU through the use of energy-efficient electricity distribution transformers', THERMIE B project, European Copper Institute, 1999;
- ▪ Eurostat, Eurelectric and ENTSOE statistics and prognoses reports
- ▪ related projects from the IEEA programmes (e.g. REMODECE).

- Consultation of the European transformer industry associations: T&D Europe data will be delivered to the extent they are available.
- Market data copper, steel and amorphous steel from the Copper Institute and Hitachi Metals/METGLAS.
- Internet sources: www.iea.org, www.eurostat.com, www.e-cigre.org, http://www.ENTSOE.org, http://www.ewea.org/, http://www.eupvplatform.org/, http://www.epia.org , www.eurelectric.org, www.erec.org,
- Public tender information as found in Official Journal of the European Union : http://simap.europa.eu/
- Extrapolation formula for losses as reported by The Japan Electrical Manufactures' Association (2005)[26] to fill data gaps.
- Individual manufacturer's enquiry to obtain data on smaller industrial transformers.

Robust data on the past and future number of transformers installed is not available. These figures will be estimated based on the EU population and electricity consumption for 1990 and the predictions for 2020 (Eurostat and Eurelectric), see § 0. These estimations will be cross-checked with the data from sector organisations.

2.2.2 Stock Data

2.2.2.1 Recent stock data– year 2004-2005

The reference year for the 'recent' stock data is 2004-2005. This is the most recent year for which complete and detailed data is available. This is also discussed and agreed with the stakeholders (meeting of July 2009).

The table below present the EU-25 (in 2005 Romania and BG were not an EU member yet) region specific data on the installed transformers (transformers in service), as collected for the SEEDT study (SEEDT, 2005) and verified with information from the sector organisation (T&D meeting 04/06/2009).

[26] The Japan Electrical Manufactures' Association (2005), presentation 'Latest Standard for Transformer Efficiency in Japan'

EU-25 region	Stock[27]				
	Distribution oil[28]	**Industry oil[28]**	**Industry dry[28]**	**Power oil[29]**	**DER dry[30]**
EAST	148100	42100	4250	65000	20000
MID	2366800	368600	101590		
NORTH	300000	35800	38960		
SOUTH	794400	334500	24680		
Total	3609300	781000	169480		

Table 2-5: Overview of the number transformer in 2005 in the EU-25 region (based on SEEDT study, 2005 and information from T&D Europe)

With: EAST: Czech Republic, Hungary, Slovakia, Slovenia,
MID: Austria, Belgium, Germany, France, Ireland, Luxembourg, Netherlands, Poland and the UK
NORTH: Denmark, Estonia, Finland, Lithuania, Latvia and Sweden
SOUTH: Cyprus, Greece, Italy, Malta, Portugal and Spain

The five MS with the biggest transformer stock are Germany, Spain, France, Italy, and Poland, with more than about 300,000 (PL) to more than 800,000 (FR) units.

Details MV/LV distribution and large industry transformers

Table 2-6 present the summary on EU-25 of the *installed number and capacity* of MV/LV distribution and industry transformers for the year 2004. According to the SEEDT data[31] and the estimations for Romania and Bulgaria the overall number of EU-27 MV/LV distribution and industry transformers is estimated at 4,6 million units in 2004.

[27] Stock= installation in service
[28] Data from SEEDT study
[29] Data from T&D Europe
[30] Calculated based on wind energy production figures (see paragraphs below) and checked with T&D Europe
[31] Source, SEEDT : Analysis of existing situation of energy efficient transformers - technical and non technical solutions, EIE/05/056/SI2.419632 (SEEDT, 2005) and info from T&D Europe (meeting 17/03/2009 and 04/06/2009)

EU-25 stock 2004 (SEEDT)				
Sector	**Rated Power (S)**	**Pieces**	**Total Rated Power MVA**	**Average Rated Power kVA**
Distribution oil	< 400	2639129	307230	
	≥ 400 kVA - ≤ 630 kVA	845107	432793	
	> 630 kVA	125047	153891	
	Total	*3609283*	*893913*	*248*
Industry oil	< 400	480596	64540	
	≥ 400 kVA - ≤ 630 kVA	176119	88119	
	> 630 kVA	124164	168295	
	Total	*780879*	*320954*	*411*
Industry dry	< 400	38416	12419	
	≥ 400 kVA - ≤ 630 kVA	67084	39906	
	> 630 kVA	63968	87817	
	Total	*169468*	*140142*	*827*
All	*Total*	*4559630*	*1355009*	

Table 2-6: Overview of the number of distribution and industry transformers in EU-25 in 2004 (SEEDT)

Verification of the data:
Household and commercial service connections are related to the MV/LV distribution transformer rating (S). Some rules of thumb, used by the network operators (e.g. those communicated by Eandis[32]) can be used to verify the SEEDT data:

- *The value of the main fuse is fixed (Imax). Currently in Belgium, 40 A is the default value for a domestic connection, many decades ago it was 25 A and the maximum is 56 A (e.g. with electrical heating or commercial service).*
- *A 0.8 Utilisation Factor (UF) is applied to account for the fact that the maximum power is seldom used. An utilisation factor of 1 is used when many connections use electrical heating or heat pump with air conditioning.*
- *A Simultaneity Factor (SF) is used that accounts that not all connections use the maximum power simultaneously:*
  - *1 for an individual connection;*
  - *0.75 for a group of detached houses;*
  - *0.6 for apartments and/or attached houses;*
  - *1 when many connections use electrical heating or heat pumps (air conditioning).*
- *Transformer rating (S) is the total sum of Imax x 230 VAC x UF x SF (single phase connections).*

  → In the assumption that the EU-27 households are connected on average with Imax of 33 A and has UF of 0.8 and SF of 0.7, this would require a total EU27 installed capacity of 900 GW (≈210500000x230x33x0.8x0.7). This fits with the capacity as mentioned in Table 2-6.

[32] www.eandis.be communication (2009).

All (99,99%) MV/LV distribution transformers are oil-immersed. For industry transformers about 80% are oil-immersed transformers. According to T&D Europe, however, about 50% of industry transformers are oil-immersed and another 50% is dry.

T&D Europe (04/06/2009) reports the following *average rating* for MV/LV distribution and industry transformers which are currently in service:

Stock EU-27	
Sector	***Average Rated Power (kVA)***
Distribution oil	250
Industry oil	630
Industry dry	800

Figure 2-6 and Figure 2-7 (source: SEEDT) contain more detailed data on kVA relative distribution in population covering three main sectors; MV/LV distribution (=utilities, oil-immersed), industry oil-immersed and industry dry type.

It is visible that utilities operate at lower ratings, while industry and particularly dry type transformers have much higher ratings in average. The lower rating of utilities can be explained by transformers that are installed in rural areas. Figure 2-6 contains more detailed country data (SEEDT, 2005).

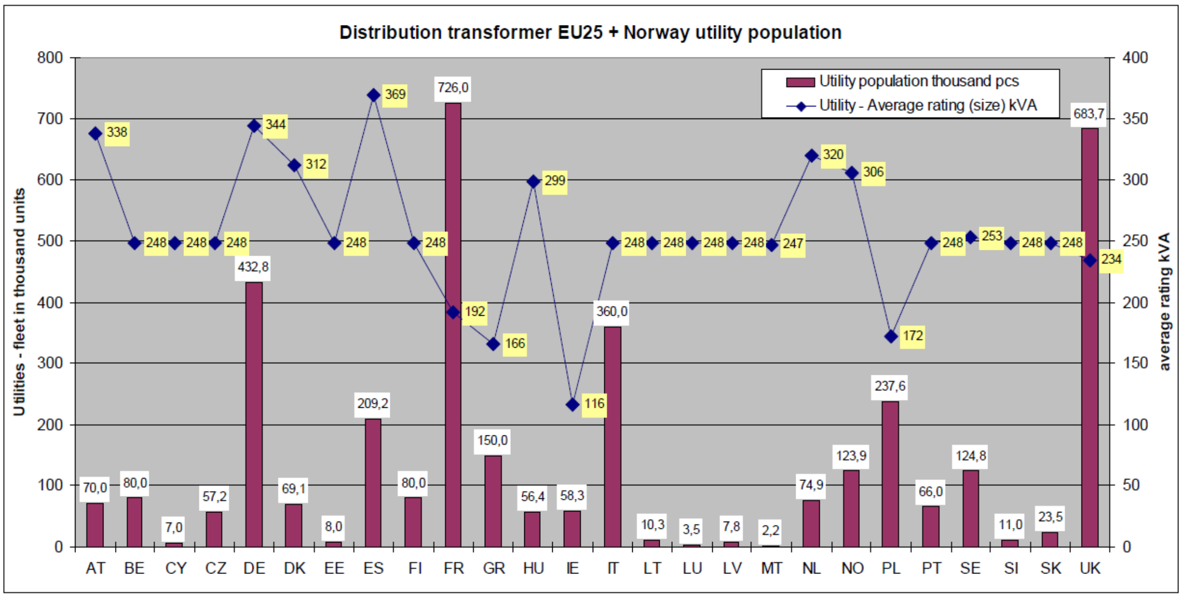

Figure 2-6: Number and average rating of EU-25 + Norway oil-immersed distribution(MV/LV) transformers (source: SEEDT)

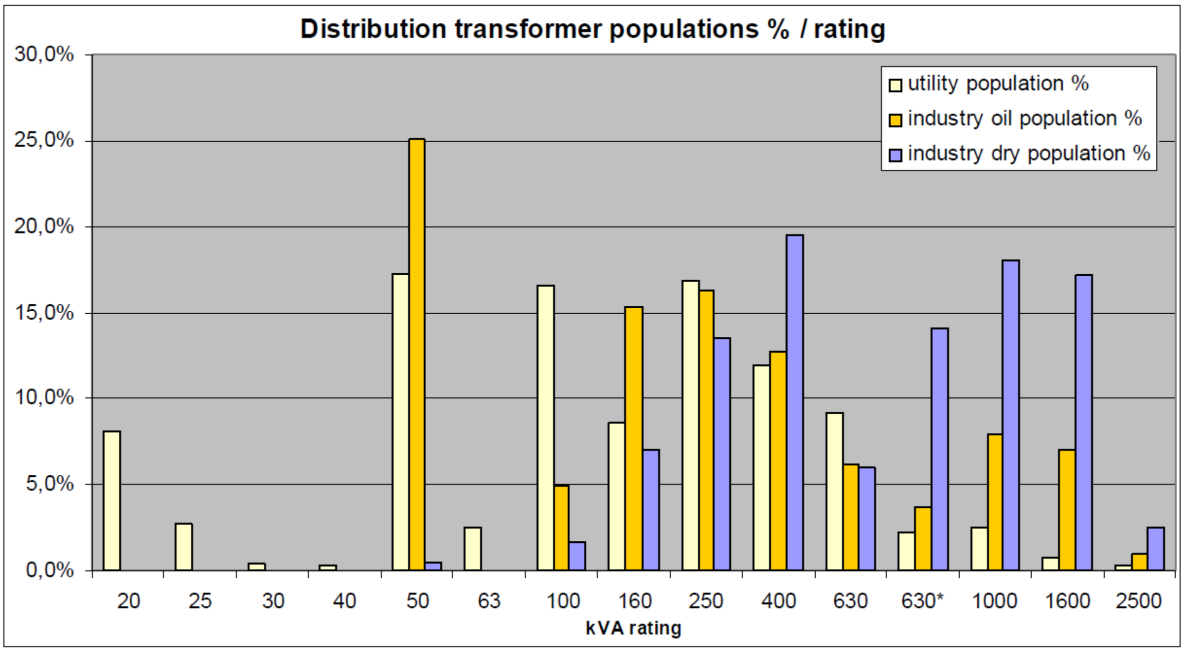

Figure 2-7: Ratings distribution across populations (source: SEEDT)

Details power transformers

In the ENTSOE[33] grid excluding the UK and Sweden 6283 GVA transformers were installed in 2005.

33 source ENTSOE: www.ENTSOE.org INFORMATION UPON THE TRANSFORMERS ON DECEMBER 31st (IN GVA) (Database: 15.04.2009 for year 2005)

The estimation for the capacity of power transformers in Sweden and the UK is calculated using the relative population in both countries compared to the population in the ENTSOE countries. These results in an additional 20% of power transformers installed in UK and Sweden, which results in about 7500 GVA power transformers installed in 2005.

T&D Europe reports about 65000 units installed in 2009. This figure is split up in power and phase transformers based on expert judgment. It is assumed that about 1% of these power transformers are phase transformers; this leads to about 64350 power transformers and about 650 phase transformers.

The average rating of a power transformer is about 100 MVA. This figures is reported as the average rating for power transformers by the sector organisation (members of T&D Europe, 04/06/2009). This does not mean this is the most sold transformer itself but it is in between the procut range, it is also the borderline between the so-called medium and large power transformers. In reports from electricity network operators (France and Belgium) the average ratings of a power transformer seems to be higher, about 180 MVA per unit.

Details DER transformers

Based on the energy production by wind turbines in 2005 (about 34 GW, see §2.2.6.6) and an average installed capacity of 2000 kVA (members of T&D Europe, 04/06/2009), the installed capacity is estimated to amount about 20 000 units.

Summary of 2005 Transformer Stock Estimate (see Table 2-7**):**

Estimations stock 2005	
Sector	***Pieces***
Distribution oil	3600000
Industry oil	800000
Industry dry	170000
Power	65000
DER	20000

Table 2-7: Estimation of the transformer stock in 2005

Note on summary: It takes into account previous data and an average 250 kVA distribution oil transformer. Values were rounded off as they are not precisely known. Increasing the stock might conflict with other data on transformer loading (chapter 3), which is already low. Increasing stock together with high load factor assumption might overestimate savings and is avoided in this study.

2.2.2.2 Past stock data – year 1990

Table 2-10presents the EU data on the estimated amount of installed transformers in 1990. Considering the figures on number of units currently installed (§2.2.2) and the electricity demand within the EU anno 1990 (§2.2.6.4), the average number of transformers installed per TWh electricity demand was estimated. One can verify the prediction for 1990 based on the age distribution (see paragraphs below for more details).

Details MV/LV distribution and industry

If we use the stock figures from the SEEDT study (figures 2004) on MV/LV distribution and industry transformers with the statistics from Eurelectric (year 2004) the following average installed units per TWh electricity demand can be calculated:

- *MV/LV distribution and industry* : 4559780 units (EU-25) for an electricity demand of 2973 TWh
  → 1534 units per TWh demand

Based on this calculated figure (units/TWh) and the electricity demand in 1990 (2280 TWh) the estimated number of MV/LV distribution and industry units for 1990 is about 3420000 units.

To verify this figure, it is also possible to make estimations for 1990 based on the age of the transformer stock in 2005. Data for Poland and the Czech Republic on age distribution of the transformer population are available and used to try to verify the calculated figure.

Figure 2-8 shows the analysis of the population age distribution for the stock transformers till 2005. This indicates that about 50% of the installed transformers are more than 20 years old.

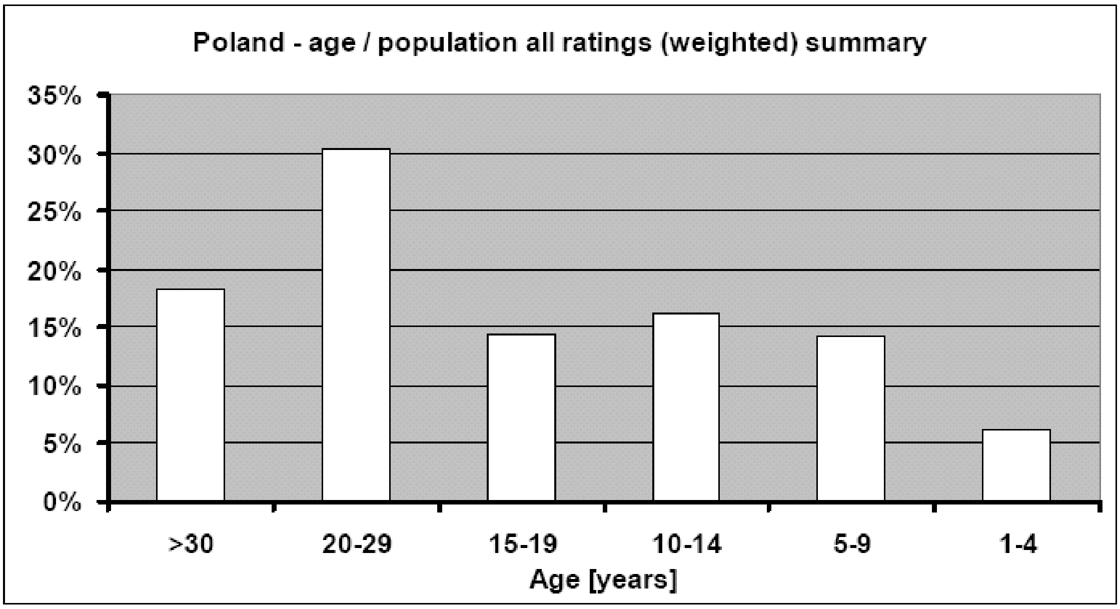

Figure 2-8: Polish number of transformers(population)/age averaged profile (SEEDT, figures till 2005)

Based on these figures, it can be assumed that 50% of the total population of 2005 was already installed in 1990. This means that > 3000000 units were installed in 1990, taking into account that about 15% of the installed capacity of 1990 will have been replaced by new ones by 2005 (average lifetime 30-40 year, see §2.2.6.1).

Details power

For power transformers, the amount is estimated on the basis of the electricity demand in 1990 compared to 2005.

Details DER transformers

For DER transformers, the amount is recalculated based on the installed capacity in 1990 (EWA, 2009)[41] which was 0.5 GW. If we assume an average capacity of 2 MVA per unit, the number of DER transformers in 1990 was 250.

2.2.3 Market Data

2.2.3.1 Recent market data – year 2004-2005

The data for transformers sold in EU-25 countries for 2004 is shown in Table 2-8.
On average, in 2004, about 137000 MV/LV distribution and industry distribution transformers have been sold annually in Europe. Together with small distribution transformers below 25 kVA and power transformers > 20 MVA, the number of transformers sold in Europe per year exceeds the 200000 pieces.

Sold transformers in EU-25			
Sector	***Rated Power (S)***	***Pieces***	
Distribution oil	< 400 kVA	55099	
	≥ 400 kVA - ≤ 630 kVA	22944	
	> 630 kVA	5884	
	Total	*83927*	
Industry oil	< 400 kVA	22887	
	≥ 400 kVA - ≤ 630 kVA	8237	
	> 630 kVA	5893	
	Total	*37017*	
Industry dry	< 400	2559	
	≥ 400 kVA - ≤ 630 kVA	5333	
	> 630 kVA	7818	
	Total	*15710*	
Power	*Average 100 MVA*	*2000*	
DER dry	*Average 2000 kVA*	*2100*	

Table 2-8: Summary of the number of distribution transformer sold on the market (SEEDT, figures 2004 and members T&D Europe (sales data 2005))

These figures are much lower than those found in the Prodcom market statistics (§2.1.2). This could be explained by the fact that the SEEDT data does not take into account the small (<25kVA) industrial transformers.

Details distribution

MV/LV distribution new transformers (market) are only about 3% of existing stock in terms of installed power (MVA). In terms of number of units, it is 2.3% only due to a trend of unit size increase.
For the energy efficiency scenario, the SEEDT study used a replacement rate of 2.5% for electricity distribution companies, equivalent to 40 years average technical lifetime.

The MV/LV distribution transformers currently sold have an average rating of 400 kVA (T&D Europe, 04/06/2009).

Details industry

Industry oil-immersed transformers market is estimated at almost 5% while industry dry type transformers market at about 10% of existing stock (in this case both units and capacity rates are similar).

For the dry transformers used in the industry, a replacement rate of 3.33% (equivalent to 30 years technical lifetime) and for oil-immersed transformers, a replacement rate of 4% (equivalent to 25 years technical lifetime) was used.

The industry transformers currently sold have an average rating of 1000 kVA for oil-immersed and 1250 kVA for dry type transformers (T&D Europe, 04/06/2009).

Details power

According to T&D Europe, the sales in 2005 of power transformers was about 2000 units; or about 3% of the currently installed units (new + replacement sales).
Figures from network operators (France and Belgium) indicate an average growth rate for new installed power transformers *of about 1.2 to max. 1.6%* of the installed capacity for the period between 2005-2012.

Details DER dry

According to ENTSOE the average growth rate of wind capacity will be about 10.5%, see §2.2.2.6. If we consider this growth rate than annually about 4 GW will be installed. This leads to an average of at least 2000 units of 2 MVA per year.

T&D Europe sale growth

T&D Europe reports *a growth figure of 3%* per year in terms of numbers of units for all types of transformers, based on a manufacturers assessment that takes into account the replacement rate of transformers (see §2.2.3).

Growth of electricity demand

For new installed transformers the growth can be estimated based on the predictions for future electricity consumption (see §2.2.6.4), the average annual growth rate of 1.6% for the 1990 data until the 2020 forecast.

2.2.3.2 Market growth in terms of New installed Sales and Replacement Sales and Stock 2020 prediction and summary on 1990 and 2005 data

New transformers are installed to replace existing transformers, so-called *Replacement Sales,* or for extending the electrical grid, so called *New Sales* or New Installed Sales.

'Replacement sales per annum' were derived from the estimated product life time, section 3.2.4 where replacement sales is 1/(life time) in percent.

New Sales of distribution and power transformers are based on growth of electricity demand. An average growth rate(gr) of *1.4 % was assumed (see section 2.2.3.1) for the period 2005-2020* and *1.9% in the past period 1990-2005*.
Rationale on growth rate assumptions:

- EU 1990 Energy demand of 2072 TWh fits with EU 2002 of 2771 TWh ($=2072/1.019^{15}$) (see section 2.2.6.4).
- EU 2005 Energy demand of 2771 TWh fits with EU 2020 of 3432 TWh ($=2771/1.014^{15}$) (see section 2.2.6.4).
- The reference year is 2005 and stock data of section 2.2.2.1 data is used.

Note:

- These figures fit very close to those found at network operators (see section 2.2.3.1);

New Sales of DER transformers is based on installed stock in 1990 (0.5 GW) (see section 2.2.2.2) being 40 GW in 2005 assumed to grow to 180 GW (see section 2.2.6.6).

Total sales (%) is the result of Replacement sales and new installed sales.

The Stock 2020 is calculated from the growth rate (gr) according to the following formula and results are summarized in:

$$\text{Stock 2020} = \text{Stock 2005}/(1+gr(\%)/100)^{15}$$

The resulting figures are summarized in Table 2-10.

Those figures are valid for the typical rating of the stock transformers and could be rescaled (values in italic) in later chapters to correct for the higher or lower ratings of the selected base case transformers.

Transformer type	S typ	Stock 1990	Stock 2005	Stock 2020	New installed sales 1990-2005	New installed sales 2005-2020	Replacement sales	Total sales 1990-2005	Total sales 2005-2020	Total sales 1990	Total sales 2005	Total sales 2020
	KVA	*K units*	*K units*	*K units*	*% p.a.*	*% p.a.*	*% p.a.*	*% p.a.*	*% p.a.*	*units p.a.*	*units p.a.*	*units p.a.*
MV/LV Distribution transformer	250	*2.714*	3.600	*4.459*	1.9	1.4	2.50	4.40	3.90	*119.438*	*140.400*	*173.891*
DER LV/MV transformers	2000	*0.25*	20	*89*	34	10.5	4.00	38.00	14.50	*94*	*2.900*	*12.967*
Industry MV/LV oil transformer	630	*603*	800	*991*	1.9	1.4	4.00	5.90	5.40	*35.590*	*43.200*	*53.505*
Industry MV/LV dry transformer	800	*128*	170	*211*	1.9	1.4	3.33	5.23	4.73	*6.708*	*8.047*	*9.966*
Power transfomer	100000	*49*	64.35	*80*	1.9	1.4	3.33	5.23	4.73	*2.539*	*3.046*	*3.772*
Phase	100000	*0.49*	0.65	*0.81*	1.9	1.4	3.33	5.23	4.73	*26*	*31*	*38*

Table 2-9: Summary of the market parameters 1990, 2005 and 2020

2.2.4 Market data on smaller industrial power transformer (> 1kVA and <100kVA) installed in the LV grid (≤ 1 kV windings)

This market is estimated at about 75000 units per year (anno 2005) with average rating of 16 kVA (typically three phase.

Based on catalogue research typical load losses (Pk) of 750 Watt and no-load losses (P0) of 110 Watt were found.

These transformers are used in a variety of industrial applications, therefore a life time of 10 years has been assumed.
This is a niche market within the transformer industry and is not expected to grow much in future. In many applications, power electronic solutions replace these smaller industrial transformers (e.g. electronic 24 VDC power supplies use in industrial automation).
As a conclusion a replacement rate of 10 % and no growth rate will be used, this simply means that the used stock is about 10 times larger compared to annual sales.

How this was obtained:

- Halogen sales anno 2005 were estimated at 6000000 units/year of 60 VA units (see lot 19 and lot 7 preparatory studies on domestic lighting and external power supplies).
- For the smaller industrial power transformer an average rating of 16 kVA has been assumed. This is in between the product range of typically 1 kVA to 63 kVA

found on the market today. However lower ratings were found in catalogues and therefore 16 kVA was preferred as a more typical rating over 30 kVA.

- Above 5 kVA industrial users normallyuse three phase system as in order to avoid unbalance in the electrical grid. Also most industrial equipment above 3 kVA is sold with three phase input voltage. Therefore a three phase 16 kVA transformer is considered more typical compared to single phase.
- It was assumed that annual sales of smaller industrial power transformers (>1kVA, see chapter 1) in turn over are of similar importance to magnetic halogen transformers (based on informal manufacturers information).
- In total rated VA an equivalent sales to magnetic halogen transformers per year would result in: 6000000x0.06/16 or 22500 units per year.
- However, after enquiry of manufacturers this figure was corrected upward to 100000 units per year taking into account market size of these transformers and the fact that nowadays more electronic transformers are used for halogen lighting.

Notes on this market assumptions:
The average might rating might be lower and unit sales higher; this compensates each other and will have a minorimpact on the further analysis.
These products are niche products and as a consequence general market data is publicly not available and might fluctuate year per year.

2.2.5 Market and stock data: conclusion

Based on the available information on recent stock and market data, electricity production and predictions for the future the following overview of past, recent and future market and stock data can be presented.

Transformer type	S typ	Stock	Stock	Stock	New installed sales		Replacement sales	Total sales		Total sales		
		1990	2005	2020	1990-2005	2005-2020		1990-2005	2005-2020	1990	2005	2020
	KVA	*K units*	*K units*	*K units*	*% p.a.*	*% p.a.*	*% p.a.*	*% p.a.*	*% p.a.*	*units p.a.*	*units p.a.*	*units p.a.*
MV/LV Distribution transformer	250	*2.714*	3.600	*4.459*	1.9	1.4	2.50	4.40	3.90	*119.438*	*140.400*	*173.891*
DER LV/MV transformers	2000	*0.25*	20	*89*	34	10.5	4.00	38.00	14.50	*94*	*2.900*	*12.967*
Industry MV/LV oil transformer	630	*603*	800	*991*	1.9	1.4	4.00	5.90	5.40	*35.590*	*43.200*	*53.505*
Industry MV/LV dry transformer	800	*128*	170	*211*	1.9	1.4	3.33	5.23	4.73	*6.708*	*8.047*	*9.966*
Power transfomer	100000	*49*	64.35	*80*	1.9	1.4	3.33	5.23	4.73	*2.539*	*3.046*	*3.772*
Phase	100000	*0.49*	0.65	*0.81*	1.9	1.4	3.33	5.23	4.73	*26*	*31*	*38*

Table 2-10: Summary of the market and stock data for 1990 – 2005 -2020

This data will be used for the definition of the base-cases (chapter 4) and the calculation of the potential energy reduction of introducing more energy efficient transformers in Europe (chapter 6). Those figures are valid for the typical rating of the stock transformers and could be rescaled in later chapters (values in italic) to correct for the higher or lower ratings of the selected base case transformers. If necessary they can be rescaled: e.g. for one or more new EU countries.

2.2.6 Additional MEEuP market parameters and important background data

Some additional market model parameters are defined. These parameters are used to correct or double check Eurostat or other available market data and to assist in predicting 2020 growth rates for the scenarios (see above) and assessment of the impact of introducing more energy efficient transformers in Europe (see chapter 6).

2.2.6.1 *Average product lifetime*

MV/LV distribution transformers have an average economic lifetime of 30 to 40 years. Industry and DER transformers have a technical lifetime of 25 to 30 years. For power transformers the average economic lifetime is higher about 30 years. However in terms of total operational cost (TOC) Japanese utilities use 19 years (Hitachi Metals/METGLAS, meeting 01 September 2009).
This parameter is used for the prediction of the replacement rate used for the estimation of the number of units sold in 2020 and explained in more detail in chapter 3 section 3.2.4
For smaller industrial transformers see section 2.2.4.

2.2.6.2 *Energy efficiency and short circuit impedance data*

Energy losses

To know what the current levels of energy losses are, figures on the efficiency class/energy losses of the currently sold transformers is presented. This will be used to set the base cases in chapter 4.

The current average losses in transformers according to the sector organisation (T&D Europe, 2009) are included in Table 2-11. In August 2010 a new enquiry was launched (see Annex D) for power transformers and sales 2005 was updated accordingly.

Sector		***Average Rated Power (S in kVA)***	***Average no-load loss (Po in W)***	***Average load loss (Pk in W)***
Distribution oil	stock	250	650	3250
	sales	400	750	4600
Industry oil	stock	630	1300	6500
	sales	1000	1700	10500
Industry dry	stock	800	2500	10000
	sales	1250	2800	13100
Power	Stock (1990)	100000	80000	300000
	Sales (2005)	100000	40500	326000
DER	stock	2000	3100	21000
	sales	2000	1760	16800

Table 2-11: Summary table on the efficiency losses of distribution transformer (T&D Europe, 2009) EU-25 and stakeholder meeting comment on DER transformers (see chapter 3) (Danmark)

Comparison between the reported average losses and the EU standard (EN 50464-1 indicates that the current stock and market of oil-immersed transformers consist of Dk/Ck//Bk load loss class and Eo to Co no-load class transformers (see Task 1 for the explanation of these classes).

Table 2-12 summarise the classes of available transformers en indicates EU’s current best level.

	Eo - -	**Do -**	**Co**	**Bo +**	**Ao ++**
Dk --		160 – 250 kVA	50 – 100 kVA		
Ck -	400 – 630 kVA				
Bk +	1000 kVA		Current EU best level		
Ak ++					

Table 2-12: Energy classes currently available transformers (SEEDT report and feedback stakeholders, august 2009)

Extrapolation or interpolation formula on transformer losses to fill data *gaps*

In principle one could perform a linear extra- or interpolation to fill data gaps on transformer losses for missing ratings (kVA), however larger transformers tend to be more efficient. More realistic formulas were presented by the Japan Electrical Manufactures' Association (2005)34, also for 50 Hz.

Rated power S	**≤ 500 kVA**	**> 500 kVA**
Oil filled	$Py=Px(Sy/Sx)^{0.653}$	$Py=Px(Sy/Sx)^{0.842}$
Dry type	$Py=Px(Sy/Sx)^{0.626}$	$Py=Px(Sy/Sx)^{0.727}$

Table 2-13: Extrapolation or interpolation formula on transformer losses

Extra background information on energy efficiency and short circuit impedance data:

Energy efficiency:

Figure 2-9 presents details on the overall energy efficiency of MV/LV distribution and industry distribution transformers for the EU-25 countries. General observations are that:

- the average energy efficiency is 98.38%;
- not all countries have the same approach on energy efficiency/load losses; however this can be related to the different load profile and electricity prices from country to country (see Task 3).

[34] The Japan Electrical Manufactures' Association (2005), presentation 'Latest Standard for Transformer Efficiency in Japan'

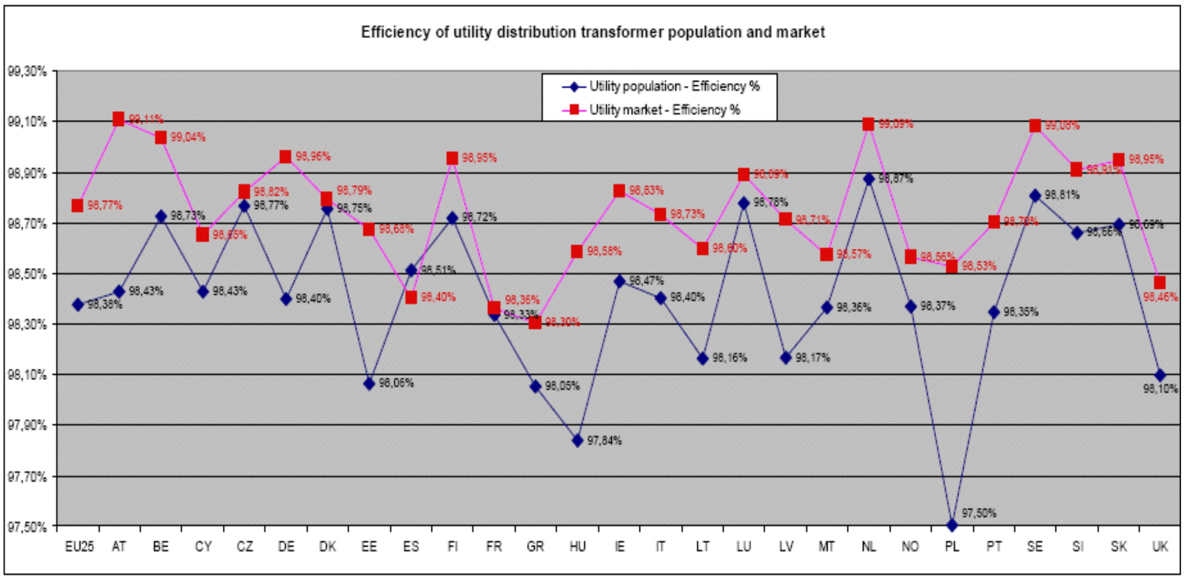

Figure 2-9: Energy efficiency of distribution transformers in EU-countries: stock and market (SEEDT)

The ERGEG position paper (ERGEG, 2008[35]) presents details on the level of the losses in the European electricity power and distribution network. General observation is that the average energy loss is 1.5%. These losses include the losses over the distribution cables. This indicates that the efficiency of power transformers is already very high, > 99%.

Typical transformer short-circuit impedance:

Transformers as well as grid connected electromagnetic generators are amongst other characterised by short circuit impedance rating (%Z) that can be found on the transformer or generator nameplate. This impedance rating is related to transformer short circuit power by S(VA)x100/(%Z) which is an important technical parameter in electrical grid protection schemes. For larger transformer (e.g. power transformers) the impedance becomes normally higher due to its construction.

2.2.6.3 Total inhabitants and households in EU-27

The table below gives an overview of the number of inhabitants for the EU-25 grouped by region –middle, north, south and east– for the reference years 1990, 2005 and 2010.

[35] European Regulators' Group for Electricity and Gas (ERGEG), 'Treatment of Losses by Network Operators - Position Paper for public consultation', Ref: E08-ENM-04-03, 15 July 2008

Region	Population (thousands)		
	1990	2005	2020
EAST	60000	57120	55948
MID	267257	282900	293617
NORTH	26569	26739	27697
SOUTH	116563	124264	136575
TOTAL	470388	491024	513838

Table 2-14: Overview of the number of inhabitants in the EU-27 region (Eurostat)

The table below includes the number of households in the EU-27 region (Source: REMODECE study).

Region	2005
	millions
EAST	39,7
MID	113,7
NORTH	9,5
SOUTH	47,6
TOTAL	210,5

Table 2-15: Overview of the number of households in the EU-27 region (source: REMODECE project)

This parameter is used for the estimation of the number of transformers installed in 1990 and the prediction for 2020.

2.2.6.4 Electricity Use Total EU-27 in all sectors

Based on the figures from Eurelectric (report 2006) the total energy demand for EU-25 (RO and BG not included as they accessed in 2007) is given in Table 2-16 for the reference years 1990, 2005 and 2020.

	Total energy demand (TWh)		
	1990	2005	2020
Final consumption	2 072.2	2 771.6	3 431.9
Network losses	155.9	199.0	241.3
EU-25	2 228	2 973.1	3 673.3

Table 2-16: Annual energy demand in EU-25 (Eurelectric, report 2006)

Based on national growth rate forecast and recorded national consumptions[36], the electricity consumption is expected to grow with an average annual growth rate of +1.6% for the 1990 data until the 2020 forecast (note section 2.2.3.2 contains more detailed data about 1990 until 2005(1.9%) and 2005 until 2020 (1.4%)).

It is not possible to tell whether the reported trends actually match the EU "20-20-20" targets: overall energy savings and cuts in CO_2 emissions may result in increased electric consumption in place of other fuels, such as petroleum in cars.

The electricity consumption thus continues to increase all over the EU. The biggest growth rates are expected in eastern and southern countries and especially in Bulgaria, Slovenia and Greece, as shown in Figure 2-10.

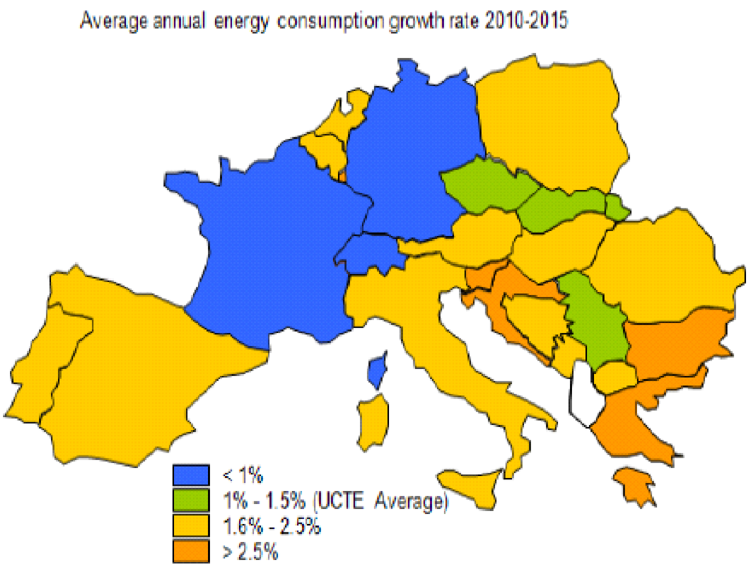

Figure 2-10: Electricity consumption average growth rate from 2010 to 2015 (ENTSOE, 2009)

Eurostat also reports on the total energy demand per sector, see Table 2-2.

[36] ENTSOE estimates are based on the national consumptions in 2007 (source ENTSOE SAR 2007 report)

	Annual demand	Avg load
	TWh	MW
Household	795	90753
Other utility (services)	758	86530
Transport	74	8447
Industry	1136	129680
Total	2763	315411

Table 2-17: Energy demand and average load per sector in EU27 in 2005.

This parameter is used for the estimation of the number of transformers installed in 1990 and the prediction for 2020.

2.2.6.5 Electricity use in households in EU-27

Table 2-18 shows 2005 electricity consumption in households by region. It is clear that middle Europe uses more electricity and thus has the greatest potential for reduction. This information is useful to estimate the transformer load factor (see chapter 3).

Region	***Electricity Consumption (TWh)***
	2005
EAST	52
MID	506
NORTH	79
SOUTH	163
TOTAL	800

Table 2-18: Household electricity consumption 2005 (Eurostat)

The following table shows the electricity consumption in 2005 based on figures from JRC (JRC, Electricity consumption and efficiency trends in the enlarged European Union, status report 2006). Based on the estimations from JRC on the potential savings till 2015[37] compared to the BAU scenario, the electricity consumption in 2015 is calculated.

[37] The energy savings potentials are based on the electricity savings which will be delivered by the energy efficiency policies and programmes.

	Electricity consumption 2005 (TWh/year)	Realistic electricity consumption 2015 (TWh/year)	Ambitious electricity consumption 2015 (TWh/year)
DESWH[38]	65	63	45
Office equipment	60	50	30
Standby	44	24	14
Residential lighting	95	79	51
Main domestic appliances	165	121	105
Commercial lighting	185	149	113
Electric motor systems	707	647	501
Total (res. + motor)	**1321**	**1132**	**886**

Table 2-19: Electricity consumption 2005 and potential electricity consumption by 2015 (BAU) (JRC , 2006)

The REMODECE project (IEEA programme) reports the same amount of residential energy consumption for 2005, viz. 799 TWh. This report also estimates a potential energy reduction of about 268 TWh per year. The estimations of the energy reduction potential of JRC indicate the same order of magnitude as shown in the REMODECE project. This energy reduction could be achieved by using the best available technology in the market.

2.2.6.6 Impact of the share of RES EU-27 on the transformer market

The share of Renewable Energy Sources (RES, other than hydro) in total electricity production in 2005 for EU-25 was 139.5 TWh (Eurelectric statistics 2005). This is about 5% of the total electricity production in the EU-25. About 34 GW (2005) of the RES capacity is wind energy (ENTSOE, 2009).

The generating capacity with RES as primary energy should continue to increase at a solid but decelerating[39] pace. The average annual growth rate for RES (other than hydro) capacity, as presented by ENTSOE[40] (2009), would be of about +17% up to 2010, then +10% up to 2015 and +5.5% up to 2020 (see Figure 2-11).

The share of RES (other than hydro) in the installed generating capacity in continental Europe would then reach about 180 GW in 2020, with ca. 136GW wind energy and 19 GW solar energy.

[38] Domestic Electric Storage Water Heaters (DESWH)
[39] RES capacity growth rate from 2006 to 2007 was +20% and +21.5% from 2005 to 2006 (source ENTSOE SAR 2007 Report)

[40] Union for the Co-ordination of Power of Electricity" (ENTSOE) is the association of power system operators in continental Europe, including: Austria, Bosnia Herzegovina, Belgium, Bulgaria, Switzerland, Czech Republic, Germany, Denmark West, Spain, France, Greece, Croatia, Hungary, Italy, Luxembourg, Montenegro, Macedonia, Netherlands, Poland, Portugal, Romania, Serbia, Slovenia, Slovak Republic

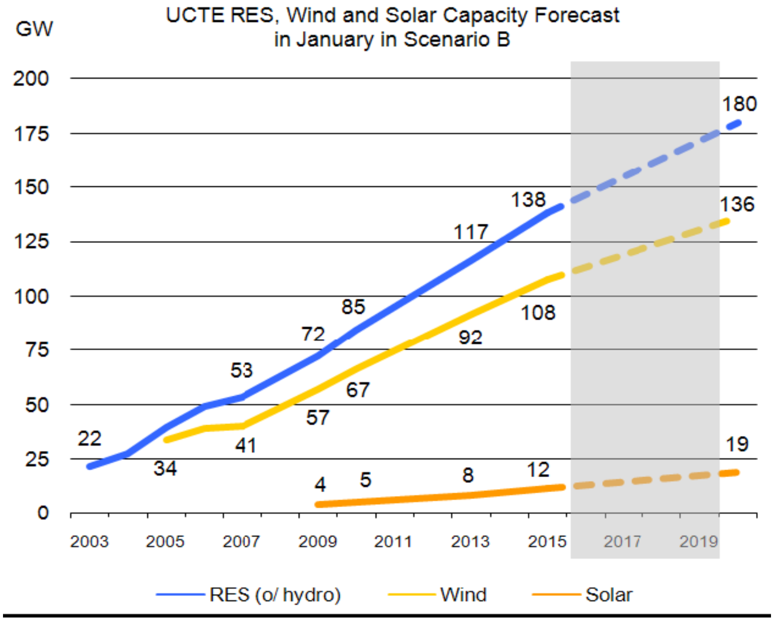

Figure 2-11: ENTSOE RES (other than hydro) generating capacity forecast under the scenario which takes into account potential future developments

According to the ENTSOE (ENTSOE, 2009) RES capacity should remain mainly wind capacity for about 75% up to 2020 (see Figure 2-11). The average annual growth rate of wind capacity would be almost +13% up to 2013 with the greatest growth rates in Eastern Europe and 6% up to 2020. According to EWEA (EWEA, 2009)[41], only 0.5 GW was installed in 1990. In 2007, turbines of the MW-class (above 1 MW) represented a market share of more than 95%. EWEA (EWEA, 2009) refers to a typical wind turbine of 2 MW.

Solar capacity should count for 8.7% of the total RES capacity in 2015 and above 10.5% in 2020. The average annual growth rate of solar capacity is foreseen to about 20% up to 2013 and 12% up to 2020.

[41] EWEA (2009): WIND ENERGY - THE FACTS EXECUTIVE SUMMARY

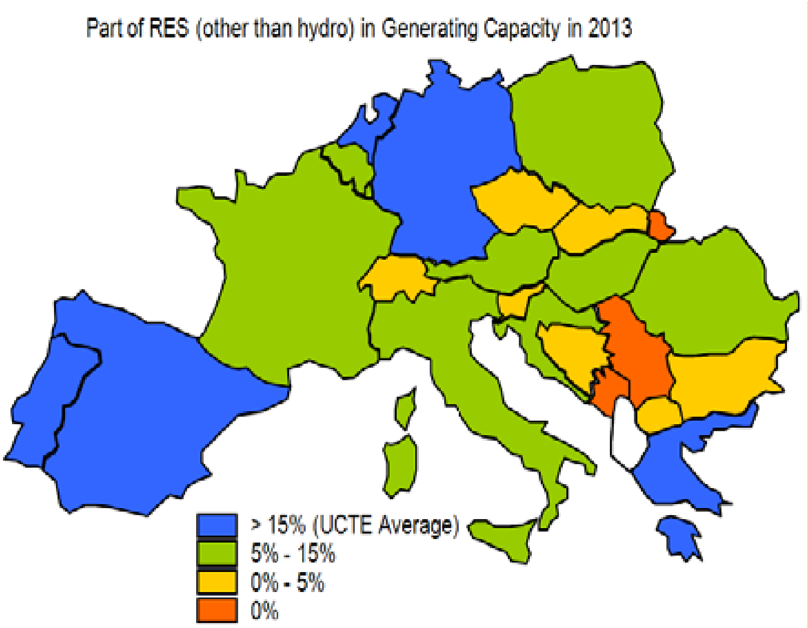

Figure 2-12: RES (other than hydro) share in the national generating capacity in 2013, taking into account potential future developments (ENTSOE, 2009)

Figure 2-12 shows that, in 2013, the biggest shares of RES capacity (other than hydro) in total generating capacity are expected in Portugal (32%), Germany and Spain (28%) and finally Greece (21%).

This parameter is used for the estimation of the number of DER transformers installed in 1990 and the prediction for 2020.

2.2.6.7 Copper market data

About 18500 kt/y of refined copper is produced worldwide, with about 13% in EU (http://www.evd.nl/zoeken/showbouwsteen.asp?bstnum=159122&location=).
The EU uses about 5000 kt of copper each year. According to the available information, demand for copper mainly comes from the electrical and electronics industries, which absorb almost 60% of total EU usage. EU accounts thus for about 27% of the world copper demand, China for more than 22%. About 3% of the copper products are related to the manufacturing of magnetic wires used in transformers (source: European Copper Institute). Copper demand is still increasing and accelerating worldwide.
Recycled copper helps to meet the growing demand for copper. Of all the copper needed across the world, 34% comes from recycling. In Europe, this figure is even higher (41%) (http://resources.schoolscience.co.uk/CDA/16plus/sustainability/copper2.html).

This information might be useful to assess the availability of the materials that are used to design energy-efficient transformers, technical details are included in related sections chapter 5.

2.2.6.8 Grain oriented Steel market data

During 2004-2008, global Grain Oriented Electrical Steel (GO) market grew strongly from 1500 kt/y to 2200 kt/y, due to a strong demand especially from emerging markets like China and India. The capacities of the global producers were fully used. In 2009, when demand slumped due to the economic and financial crisis, GO capacities were further increased mainly in China to worldwide 2500 kt/y. In the EU, the GO market was at 360 kt/y in 2008, with capacities of the 4 EU-suppliers of 420 kt/y.
With regard to High permeability Grain Oriented Electrical Steel (HGO), there are 8 suppliers worldwide, thereof two producers in the EU. The global HGO supply in 2009 was at nearly 700 kt/y, thereof 130 kt/y in the EU.
Global GO demand is expected to grow to roughly 2700 kt/y in 2015; GO capacities will be further expanded to over 3000 kt/y worldwide, thereof 1000 kt/y for HGO. In the EU demand and supply are expected to grow moderately, with a stronger focus on HGO.

This information might be useful to assess the availability of the materials that are used to design energy-efficient transformers, technical details are included in related sections chapter 5.

2.2.6.9 Amorphous Metal Distribution Transformers (AMDT)market data

In the early 1980s rapid increases of the energy cost prompted the introduction of the production of amorphous core steel (Copper Institute and Hitachi, feedback stakeholder meeting September 2009). Amorphous metals are another class of materials compared to grain oriented silicon steel. Amorphous metal is produced by cooling down from the liquid state so rapidly that there is no time to organise into a crystalline structure, Due to their significant different technical charteristics also another transformer manufacturing technique is needed. More technical details are described in the related section in chapter 5.

The production of this amorphous steel, has led to the development of amorphous metal transformers (AMT) in the US in the 1980s. These novel and highly energy-efficient units were more expensive but have significantly lower operating costs than conventional units. Due to the characteristics of amorphous metals other cutting/punching tools are needed in the transformer manufacturing process, since the traditional ones would wear out in a very short period. The materials are also very mechanical stress sensitive and require annealing under magnetic field to achieve optimum performance. Another drawback is that it has 20% lower magnetic saturation, resulting in increased core and transformers size.

From The 1980's till 1995, over 500 000 units were installed in the US with satisfactory field experience. In the late 1990s, the demand for these transformer types disappeared in US as restructuring (deregulation) set in. However, the AMDT has been very active in Asian countries, like India, China and Japan. Amorphous steel is now widely manufactured and used in China and US. N. Cristefaro (1998) indicated that about 1 250 000 AMDT are installed worldwide.

The following paragraphs describe the current AMT activities in different countries (EPRI, 2009[42]), see also Figure 2-13:

Japan: Japan was the second country after the United States to use this highly energy efficient product. Currently, there are at least four Japanese manufacturers offering

[42] EPRI (Electric Power Research Institute) White Paper, Amorphous Metal Transformer: next steps, CA USA, July 2009.

AMTs commercially. It is estimated that Japan has over several hundred thousand units installed in the field and operating satisfactorily for over 18 years.
Recently, several utilities removed 30 units from the field that were in service for 10 years or longer and conducted core performance tests. All showed stable performance. X-ray diffraction patterns did not show any crystallization activity, further confirming that the material had maintained amorphous status.
Hitachi Metals, the parent company of Hitachi Metglas (the U.S. producer of the metal), has now started producing amorphous metal in Japan. The joint Hitachi/Metglas group is the worldwide biggest promoter of amorphous technology in distribution transformers. Worldwide market share of these transformers is quite significant with about 3 million units and a few hundred thousand three phase units. It represents about 5% market share worldwide but not in Europe of distribution transformers. Hitachi-Metglas's capacity of amorphous ribbon is at the level of 50 000 tons yearly in 2007 and a capacity of 100 000 tons scheduled in 2010. The 2007 production is equivalent to about 60 000 units of 400 kVA three phase transformers, which is about 50% of the European distribution transformers market. The market share of amorphous metals on the global market of core materials (=GO + amorphous metals) is at 2,5%.
India: India was the third country to adopt this product and currently is the largest user. It installs as many AMTs annually as the rest of the world combined. Currently, it has the largest installed base, surpassing the United States. The Bureau of Energy Effi¬ciency of the Ministry of Power of India has established a "5 star" efficiency scale for distribution transformers (see also chapter 1). AMT meets a 5-star rating. The Bureau also has proposed that state electric boards and industry specify 3 stars as a minimum requirement. However, the purchase decision is left to the state electric boards, and AMTs are justified on total ownership cost. There are three manufacturers of AMTs in India while others are have already investing in AMT equipment and will begin production in 2010. In India, the market is dominated by ratings below 200kVA (almost 80% share in 2009) and utilities are the largest buyers. Hence the AMT lobby (M/S Hitachi & their OEMs) are focusing on market below 200kVA. Generally, 1-ph transformers are pole mounted, hence there is no conflict reported between weight & efficiency. In terms of number of AMT, India might be largest user since their average KVA size is small nevertheless China is definitely larger in terms of installed KVA. According to an AEP (Tina Wang, 2010) estimate the ratio would be about 1:2 to 1:3 in terms of installed KVA in recent few years.
China: China was a latecomer in adopting this product, but is now the world's largest purchaser of amorphous metal. . . As of today, there are close to hundred Chinese transformer manufacturers who are certified to produce AMT. About a quarter of them are equipped with amorphous metal core production capability and hence able to produce AMT directly from amorphous metal ribbon. The remaining manufacturers purchase amorphous metal cores in order to make AMT. China has started to massively install AMT in a number of energy intensive provinces since 2005. Currently, over 20 million kVA AMTs are installed every year[43] and the total installed AMT capacity in China is estimated to be about 70 million KVA, which is the largest among all countries in the world. Besides Hitachi Metals company, the Beijing-based Advanced Technology & Materials Co., Ltd., a listed company on the Shenzhen Stock Exchange, can also manufacture the amorphous metal ribbon for AMT application. It is planning a drastic increase in capital expenditure. Lately it has been announced in the Chinese press that this manufacturer will have a 40.000 ton capacity set up by the end of 2010. In addition to these two companies, there are a number of smaller Chinese companies who can produce limited amount of such ribbon.anno 2008. Since 2010[44], the growth in China has been very significant and for 2010 the projected installation in China will be about 30,000,000KVA. The official standard governing oil-type AMT in China is JBT-

[43] Li, Jerry (2008), Deployment of Amorphous Metal Distribution Transformer in China, China Electric Power Yearbook 2008, P.793-795, China Electric Power Press (In Chinese)
[44] As mentioned by Asia Energy Platform (AEP) on behalf of Li Jerry in 2010

10318 (see chapter 1). However, it is common that Chinese utilities usually require something more stringent in terms of core loss so they specify, for example, S15 -10%, meaning a further 10% down from the standard S15 core loss. Zhixin, for example, have short-circuit test cleared for oil-type AMT up to 3500KVA AMT. For dry-type AMT, 1000-2000KVA are common and also passed short-circuit test, but noise will become quite significant for such size.

Taiwan: Tai Power started evaluation and purchase of AMTs in the mid 1990s. Tai Power is now a significant user of AMTs. There is an AM core manufacturer in Taiwan, and three manufacturers of transformers are AMT suppliers.

Bangladesh: Bangladesh has purchased AMTs and also has a significant installed base. Many of these are procured with aid money, and AMT has been justified based on units having lower total ownership costs. There is no manufacturer of AMT in Bangladesh.

Other Asian Countries: Several other Asian countries are using AMTs, and a few additional ones have started the evaluation process. Both KEPCO in Korea and PHELEC in the Philippines are now significant users of AMTs. Australia and Thailand have initiated adoption and are now purchasing small quantities of AMTs.

Other Asian Countries: Several other Asian countries are using AMTs, and a few additional ones have started the evaluation pro¬cess. Both KEPCO in Korea and Meralco in the Philippines are now significant users of AMTs. Australia and Thailand have initi¬ated adoption and are now purchasing small quantities of AMTs.

Europe: In Europe, distribution transformers use “stack core” construction where the core is formed by stacking laminations of steel. This manufacturing process doesn’t lend itself to adopting AMTs because they require a “wound” construction. Thus, adoption of AMTs in Europe is somewhat slow. In 1997 about 161 amorphous transformers were installed in Europe[45],[46] and were produced by European manufacturers. Recent analysis of these transformers in Belgium showed that there was not any core performance degradation after more than a decade. More recently the energy company ENDESA(Spain) started again a pilot project with 20 units of amorphous core transformers (400 kVA). Other major utilities are following this trend and are currently evaluating AMT(ENEL, EdF, ..). According to the most recent news ABB is opening a new transformer manufacturing plant in Brilon, Germany in March 2010. This facility specialises in the manufacturing of a cast-coil dry-type transformer that operate on an amorphous core[47]. In Europe there is only one producer of amorphous metal (Vacuumschmelze, 10 kton), but they currently produce only speciality alloys for other applications (power electronics, ..).

South America: Brazil is the first South American country using AMTs. An Indian AMT company has started manufacturing AMTs in Brazil. In response to this market entry, an AM core manufacturer has emerged, supported primarily by other transformer manufacturers. Other transformer manufacturers will source AM cores from this core manufacturer and produce AMTs.

North America: The United States has one of the largest installed bases and the longest operational experience.. With the new DOE regulation in place the market for Amorphous Transformers re-surfaced in 2010, approching the levels of the mid 1990.

Canada has relatively high loss evaluation factors. Numbers are high enough to justify AMTs even at significantly higher first cost. Thus, several Canadian utilities have started evaluating this product. One AM core manufacturer has emerged, and it is expected that most transformer manufacturers will source AM cores and produce AMTs.

Recently, several transformer manufacturers in North America have initiated the production of AMTs in small quantities. Mexico has one AMT manufacturer.

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[45] Energie publication series, ‘The scope for energy saving in the EU through the use of energy-efficient electricity distribution transformers’, THERMIE FP 5 project report, 1999.

[46] Segers, G. Even, A. Desmedt, M., ‘Amorphous core transformers: behaviour in particular network conditions and design comparisons’, CIRED. 14th International Conference and Exhibition on (IEE Conf. Publ. No. 438), 1997.

[47] http://www.abb.com/cawp/seitp202/fb0fc8bb128af642c12576e9001d139e.aspx

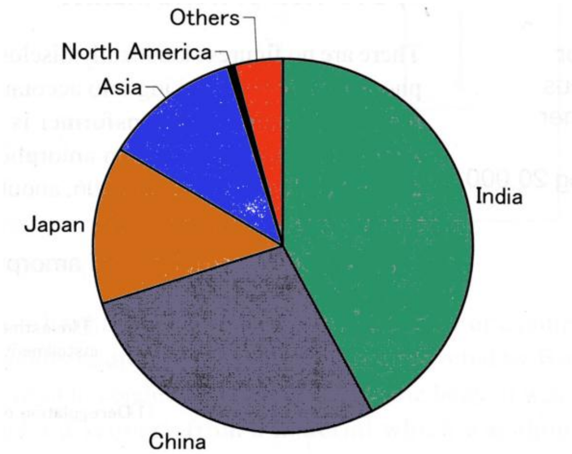

Figure 2-13: Amorphous transformer distribution by countries (2006) (Effitrafo ENDESA, May 2008[48])

Figure 2-14 shows the market trend of amorphous material for transformers till 2006 (Effitrafo ENDESA, May 2008[49]). This figure indicates that about 22 000 ton of amorphous steel is used. Hitachi Metals/METGLAS (feedback first stakeholder meeting, September 2009) presented figures which indicates that the production capacity of amorphous stock in 2008 was 50 kton and will rise to 100 kton by 2010 (it however not indicted how much of this amorphous steel goes to the transformer market).

If we take 400 kVA as the average rating of transformers installed, at 600 kg core material, about 37 000 amorphous transformers are produced each year (based on figures 2006). This about 1.2% of the total annual sales worldwide. This will only increase: given the expected market growth indicated by Hitachi the AMT market share could even be doubled or more by 2010.

[48] Effitrafo, ENDESA pilot project 'Amorphous versus Conventional core technology in Distribution Transformers', III International Conference on Energy Innovation, Barcelona, 30th May 2008

[49] Effitrafo, ENDESA pilot project 'Amorphous versus Conventional core technology in Distribution Transformers', III International Conference on Energy Innovation, Barcelona, 30th May 2008

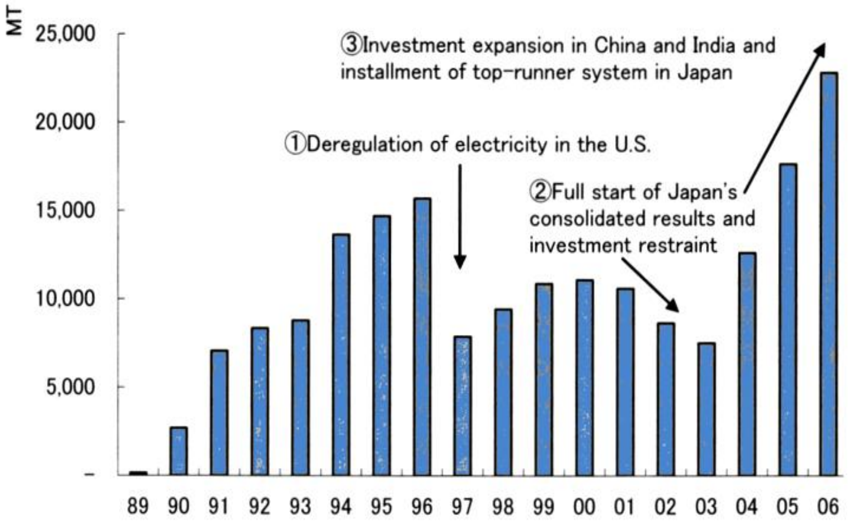

Figure 2-14: Market trend of amorphous transformer material for transformers (2006) (Effitrafo ENDESA, May 2008[26])

This information might be useful to assess the availability of the materials that are used to design amorphous metal transformers, technical details are included in related sections chapter 5.

2.3 Market trends

These paragraphs provide insights in the latest market trends which will be useful to identify potential base-cases and evaluating their improvement potential in task 6.

2.3.1 Trend to increase the stock of residential distribution transformers

Total electricity consumption in the residential sector in the EU-27 has grown during recent years at almost the same rate as the economy. Similar trends are observed in the tertiary sector and to a lesser extend in the industry (JRC, 2007).

However, it is expected that the energy consumption in the residential sector will decrease during the coming 10-15 years. Indeed, energy efficiency policies and programmes in EU and national level lead to the replacement of installed less energy-efficient equipment with new more efficient equipment. Within 10 to 15 years the whole stock will be replaced and the full effect of the policy measures will have taken place. This will lead to annual electricity savings (see § 2.2.6.5).

On the other hand, the distributed electricity production will increase. On-site production minimises power and distribution losses as well as the related costs, which are currently a significant part (> 30%) of the total electricity cost. Distributed generation will play an important role in future electricity production, including many RES and CHP plants. Belgian figures on CHP for instance (Elia, 2005[50]) indicate a growth of about 700% compared to 2003.
These plants will supply small-scale power at sites close to the users. This trend to more distributed power generation will require the installation of new distribution

[50] Elia, 'Ontwikkelingsplan 2005-2012, 17 september 2005 - Belgium

transformers. This trend is reflected in the projected market figures (see § 2.2.6.5 and § 2.2.6.6).

2.3.2 Trend to increase the distribution transformer stock utilised in decentralised renewable energy production

In 2001, the EU adopted a Directive on electricity production from RES. This Directive includes national targets for the Member States regarding the future consumption of electricity produced by RES. Within this regulatory framework, 22% of the electricity consumption should be produced from RES by 2020. This growth in renewable energy output will require additional distribution transformers to secure a stable energy supply.

This trend is reflected in the projected market figures (see 2.2.6.6).

2.3.3 Trend towards more power transformers installed in offshore wind farms

Wind energy is an important RES, with some areas of Europe achieving a significant percentage of total generation capacity. Currently the largest wind turbine delivers up to 4.5 MW with typical commercial installations rated at 1.5-2.5 MW. Growth in wind power generation is significant (see § 2.2.6.6). Belgian figures (Elia, 2005) indicate an average growth of 300% compared to 2003 for Belgian off-shore wind parks. The installation of new wind farms will require new distribution transformers to supply this energy to the electricity net or to the users.

This trend was not reflected in the projected market figures on power transformers.

2.3.4 Trend towards more power transformers used for European interconnection lines

Electricity networks across EU are 40 years old or more and are fast approaching the end of their design lives. Many national grids require substantial investment in updating, with the replacement of existing networks and the interconnecting of networks.

The EU has set up a framework for the transition towards interconnected grids using a common European planning and operational systems. In its first guidelines for a trans-European energy network, the EU has identified 314 infrastructure projects which have significant impact on the cross-border power. The EU will need to invest €6000 million for electricity power to address the priorities of this trans-EU energy network guideline.

This trend was not reflected in the projected market figures on power transformers.

2.3.5 Trend towards the use of electronic power supplies instead of smaller industrial control transformers

Power supplies of industrial control cabinets nowadays use more electronic power supplies (e.g. 24 VDC) instead of control transformers (e.g. 24 VAC).

2.3.6 Trend toward more energy efficient distribution transformers at DSO/TSOs

An important market trend is that DSO/TSOs pay more attention to energy and cost savings approaches, this is also explained in more detail in the user related chapter 3 in section 3.1.4.

2.3.7 Duration of the redesign cycle of a distribution transformer

2.3.7.1 Timeframe to produce more efficient transformers using the same production lines

The timeframe to produce new transformers on the same production line is variable and depends of the manufacturer, the needs of the market and the specifications required by the purchaser. The time to make type test and special test is also important. However, the timeframe to achieve such modification is between 3 months and 1 year (T&D Europe, 04/06/2009).
It is necessary to note that new transformers with lower losses lead to bigger transformers with bigger components. The time necessary for the production of transformers increases and the capacity to produce the number of unit decreases. However during the last years the transformers manufacturers have increased their production capacity. The replacement of the currently installed inefficient transformers probably will not be problem.

2.3.7.2 Timeframe to produce more efficient transformers and change production lines

In this case, the time frame will be much longer. In the case of amorphous transformers, the time varies with the availability and lead time of the production equipment needed. The existing production equipment for coil manufacturing, coil/core assembly installations, active part assembly and the tanking may need some adjustment. Some specific installations like material cutting and annealing need to be added.
Lately improvements have been made in order to:

- Meet the IEC standards, especially with regards to short circuit behaviour.
- Develop designs that allow power ratings up to 5000 kVA for 5 leg oil transformers and 3000 kVA for 3 leg dry transformers
- The capacity of the manufacturers of amorphous steel was increased to supply a significant share of transformers to be installed. The current capacity of amorphous metal is on the same order of magnitude as total distribution electrical steel demand in the EU.

These improvements will allow the transformer manufacturers to produce amorphous transformers within the next year in certain companies. For other companies it can take up to 3 to 5 years.

2.3.8 Major manufacturers and market players

The main industry players for this product group are big international groups like ABB, Siemens, Areva, Schneider Electric, and some large/medium size companies like Cotradis, Efacec, Pauwels, SGB/Smit and Transfix, Transformer manufacturers from outside the EU include GE, Hitachi (Japan) and Vijai (India).

Their respective material suppliers for winding wires and foil are a multitude of European and non European companies and for electrical steel. For GO electrical steel there are 4 suppliers in the EU (ThyssenKrupp Electrical Steel, Orb Electrical Steels, ArcelorMittal Frydek Mistek, Stalprodukt) and 8 producers outside the EU (NLMK/Russia, Nippon Steel/JP, JFE/JP, AK Steel/USA, ATI/USA, Baosteel/CHN, Wisco/CHN, Anshan/CHN, Posco/S. Korea), ArcelorMittal Inox/Brazil). .
T&D Europe is the representative of the European Transformer Manufacturers, regrouping the Austrian, Belgian, British, French, German, Italian, Spanish, Portuguese and the Netherlands's National Associations.

Nevertheless, SMEs are also active in transformer production, especially for niche smaller industrial applications transformers.

Today, amorphous steel transformers are manufactured in significant quantities by Asian and Indian companies, such as Hitachi, Zhixin and Kotsons. In Europe investments in amorphous steel transformers equipment will probably accelerate, beginning in 2009.

Transformers for industrial applications are most often sold and installed by SMEs in a B2B market and in some cases SMEs have service contracts with utilities for installation. They are not subject to any public tender.

For utility sales, all calls for offers must be published in the European journal; common EU-wide rules apply for the granting of orders. Usually these tenders run for a delivery period of 2 years, with substantial volumes and cover the whole range of the possible transformer ratings.
These tenders are subject to the utility's specification which can vary in transformer performance, rating and energy efficiency. Needless to say that there is no common energy efficiency specification EU wide yet. Sales to utilities are often directly from the manufacturer to the MV/LV distribution.

Smaller transformers are mainly produced by European SMEs. It is a niche market and clients often directly order with the manufacturer. It is estimated that there should be about 50 SMEs active in production; often these companies have only a few employees.

For market players on Amorhous metal production and transformer manufacturers see next section.

2.4 User expenditure base data

2.4.1 Transformers prices

The price of a transformer depends on the price of the raw materials, and of course the specific wishes of the client. Active materials represent about 50% of the price; all materials (incl. tanks etc.) represent about 70% of the transformer price.

As the market of raw materials is very dynamic and specification of transformers differs from client to client, average investment costs are hard to compare.

The manufacturing costs can be defined as:

$$C_{manufacturing} = C_{fixed} + C_{core}M_{core} + C_{coil}M_{coil}$$

with:

$C_{manufacturing}$ = the manufacturing cost
C_{fixed} = the transformer fixed cost
C_{core} = the core material cost
C_{coil} = the cost of the raw material of the coil
M_{core} = the total mass of the core in kg
M_{coil} = the total mass of the coil in kg

Material pricing is critical because the transformer cost is calculated based on the bill of materials that includes steel, conductor, mineral oil, tank dimensions, etc. If material prices increase so will the price of the transformers.

The SEEDT study[51] presented graphs on the influence of the cost of raw materials on the transformer investment cost, see Figure 2-15 and Figure.

[51] Strategies for development and diffusion of Energy-Efficient Distribution Transformers in Europe, Seedt WP4 – Deliverable D9, Analysis of potential for energy savings, June 2008

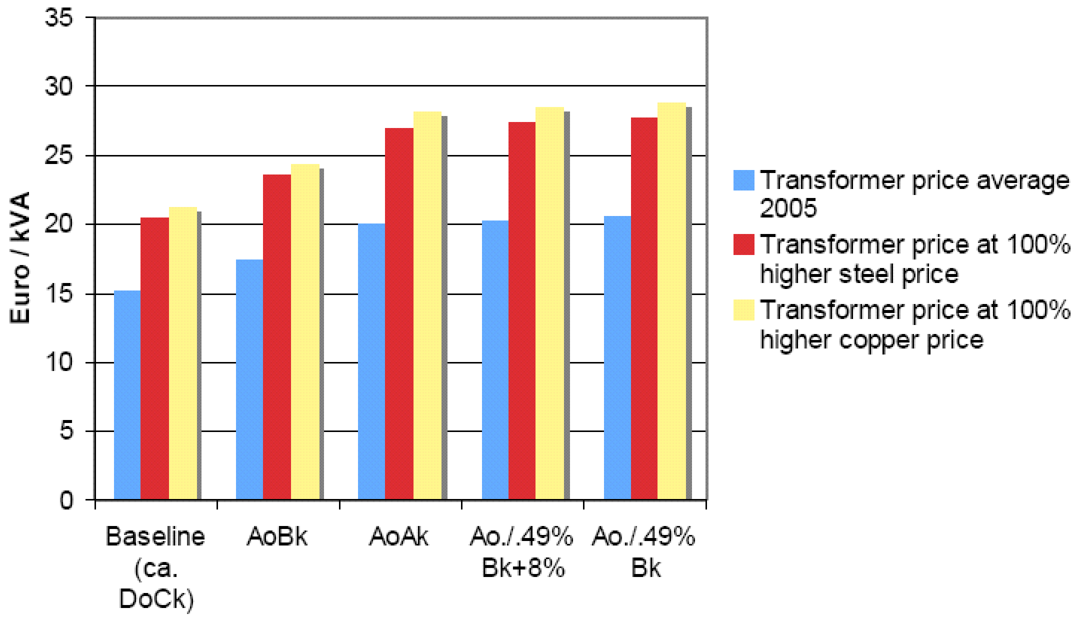

Figure 2-15: Oil transformer prices in different technologies (SEEDT, June 2008)

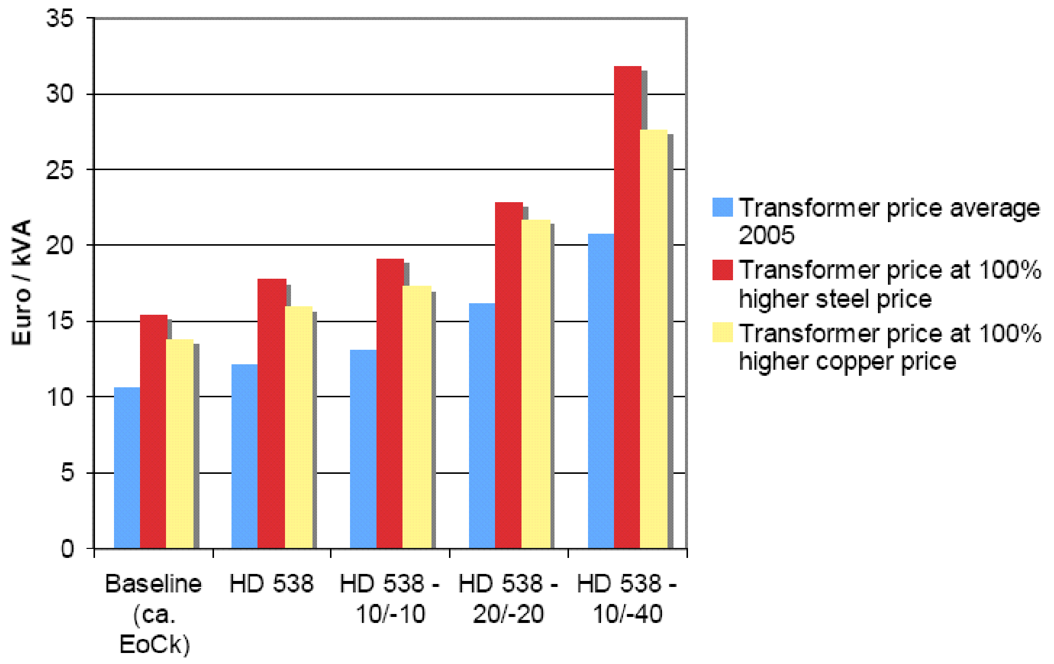

Figure 2-16: Dry transformer prices in different technologies (SEEDT, June 2008)

Furthermore, energy efficient transformers tend to incorporate more materials (e.g. kg of core steel and conductor), as shown in the figures above, making the impact of more expensive materials even more significant at higher efficiencies.

T&D Europe presented the following example of evolution of price for oil-immersed transformers (meeting T&D Europe 04 July 2009):

- class EoCk 100%
- class CoCk115%

- class BoCk130%

This indicates an increase of the price from EoCk to BoCk of about 30%. However, the SEEDT figure shows an equal increase of the price from DoCk to AoAk. Thus these figures do not correspond and indicate that the SEEDT figures are underestimated or the T&D Europe examples are overestimated.

The SEEDT-study (June 2008[54]) indicates that ten years ago, amorphous transformers were more expensive than the European average transformers (with CkCo losses) by a factor of 2 or more and that today, this proportion has reduced to a factor of 1.5 or less.

The observations from Deutschen Kupferinstitut (DKI) for 250 kVA are:

- EoCk= 100%
- DoCk= 110%
- CoCk= 122%
- BoCk = 135%
- AoAk= 160%

The US department of Energy published that an increase of the energy efficiency with 1% increases the transformer price with 73% (DOE, 2001[52]), see Figure 2-17.

[52] US Department of Energy (DOE), 'Dustribution Transformer Standards Rulemaking, December 2001)

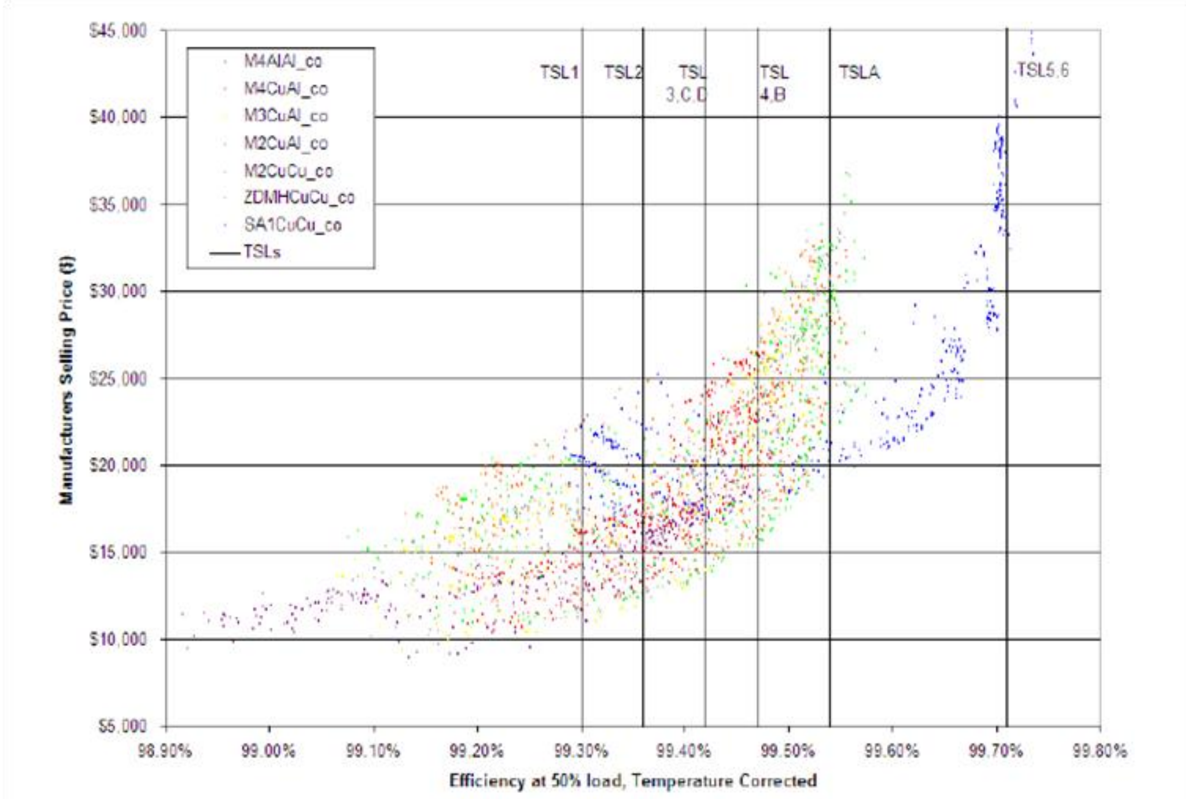

Figure 2-17: Average transformer price versus efficiency/ type 1500 kVA three-phase 60Hz liquid-immersed[53]) (DOE, 2006)

2.4.2 Transformer commodity prices

From the previous section, it is clear that the transformer prices are strongly dependent on the transformer commodities prices.

T&D Europe provides monthly 'Transformer Commodities Indices' that are used by the sector to index transformer prices. Cotrel, the transformer manufacturer association, published the following price indications (see Figure 2-18).

[53] Primary: 24940GrdY/14400 Volts (125kV BIL); Secondary: 480Y/277 Volts; T Rise: 65°C; Ambient: 20°C; Terminal Configuration: ANSI/IEEE C57.12.26, Loop Feed; Winding Configuration: Lo-Hi; Core: Wound core distributed gap, 5leg; Taps: Four 2½ percent, two above and two below the nominal; Impedance Range: 4.5-7.0%. (called "Design Line 5").

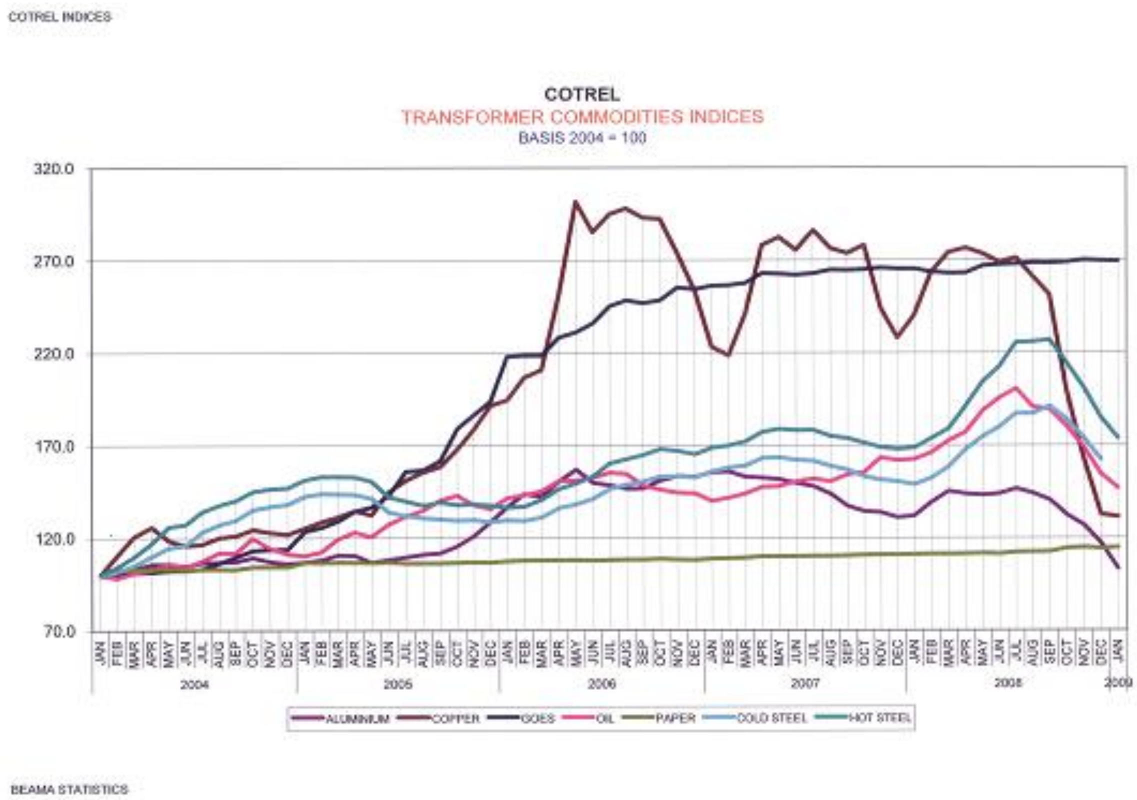

Figure 2-18: Cotrel Transformer commodity prices

The figure shows that GO steel price level of 2007 being roughly 180% of the 2005 price level. Copper prices show an even higher level. These variable market trends on steel prices were confirmed by T&D Europe (meeting 17/03/2009).
Confirmed sources indicate that if the price for silicon steel were €3,50 to 4,00 per kg then amorphous material would be slightly lower.
The SEEDT-study (June 2008[54]) mentions commodity prices of

- low loss magnetic steel 2 500 - 3 000 € / tonne,
- copper 6 000 - 7 000 € / tonne

In the current economic context (2009-2010) prices are subjective to strong fluctuations[55].

An overview of the main transformer material prices is included in Table 2-20(source: DOE (2007)[56]). More technical details on those materials can be found chapter 5. In this table core steel uses the US designations (M2, M3, ..), the equivalent EN designations can be found in section 5.1.2.3. The marked up price includes typical material processing.

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[54] SEEDT-study, Selecting Energy Efficient Distribution Transformers A Guide for Achieving Least-Cost Solutions PROJECT Nº EIE/05/056/SI2.419632 First Published June 2008 Prepared for Intelligent Energy Europe Programme Strategies for Development and Diffusion of Energy Efficient Distribution Transformers by Polish Copper Promotion Centre and European Copper Institute

[55] http://www.tdeurope.eu/en/raw-material/transformers-indices/current-month/ or http://www.zvei.org/index.php?id=488

[56] Technical support document: Energy efficiency program for commercial and industrial equipment: electrical distribution transformers', U.S. Department of Energy (DOE), September 2007

Material	2002-2006 average 5 year material price in €/kg	2002-2006 average 5 year marked up material price in €/kg
Liquid immersed transformers		
M2 core steel	1.96	2.82
M3 core steel	1.79	2.58
M4 core steel	1.72	2.48
M5 core steel	about 3.00	
M6 core steel	1.55	2.23
mechanically-scribed core steel	2.75	3.95
amorphous - finished core, volume production	2.5 - 3.61	5.17
copper wire, formvar, round 10-20	4.36	6.30
copper wire, enamelled, round 7-10 flattened	4.42	6.37
copper wire, enamelled, rectangular sizes	4.73	6.82
aluminum wire. formvar. round 9-17	2.58	3.72
aluminum wire. formvar. round 7-10	2.62	3.77
copper strip. thickness range 0.020-0.045	4.54	6.55
copper strip. thickness range 0.030-0.060	4.41	6.35
aluminum strip. thickness range 0.020-0.045	2.87	4.14
aluminum strip. thickness range 0.045-0.080	2.82	4.07
kraft insulation paper with diamond adhesive	2.79	4.02
mineral oil (per liter)	1.00	1.50
tank steel	0.74	1.08
Dry-type transformers		
domain refined core steel	2.14	3.11
M3 core steel	1.81	2.60
M4 core steel	1.72	2.48
M5 core steel	1.64	2.36
M6 core steel	1.60	2.31
M19 core steel (26 gauge)	1.03	1.49
M36 core steel (29 gauge)	0.95	1.35
M36 core steel (26 gauge)	0.86	1.25
M43 core steel (26 gauge)	0.81	1.18
rectangular copper wire 0.1 x 0.2. Nomex	4.85	6.99
rectangular aluminum wire 0.1 x 0.2. Nomex	3.48	5.03
copper strip. thickness range 0.20-0.045	5.05	7.28
aluminum strip. thickness range 0.20-0.045	2.87	4.14
Nomex insulation	30.64	44.16
Cequin insulation	18.70	26.95
impregnation (per liter)	3.71	5.22
winding combs	31.36	44.11
enclosure steel	15.99	23.07

Table 2-20: Overview of material prices for liquid immersed and dry-type transformers in €/kg (DOE, September 2007, input from stakeholders (August-September 2009)

2.4.3 Electricity prices

Electricity prices vary significantly in EU. In each country also these prices are influenced by the consumer level. Eurostat has different data for the industry sector, considering average prices and prices for SME's. For this study it is proposed to use the prices of large industrial consumers except for DER transformers, because the transformer losses are either paid by the network operator for domestic users and for large industrial users by themselves.

Note (9/2010): At the very end of the study some TSO/DSOs remarked that they paid in the past much lower prices (0.045€/kWh) and doubted the economic sense of chapter 7 proposed policy measures. Nevertheless it is proposed to remain the analysis in this study with those electricity prices that were proposed and discussed in two stakeholder meetings before (2009, 5/2010). The rationale is that by using the large industrial consumers price a more fair economic comparison between all EU27 energy saving and renewable energy production options is obtained to achieve EUs 20/20/20 target. The large industrial consumer price is as mentioned hereafter already below some costs to produce renewable energy (photovoltaic, wind, ..), hence higher prices could be argued as well. Moreover a future price increase might be expected as well.

	2005	**2006**	**2007**	**2008**
Medium size households	0.1013	0.1068	0.1173	0.1211
Medium size industries	0.0672	0.0752	0.082	0.09
Large industrial standard consumers	0.0589	0.06715	0.07115	0.078
Average	0.0848	0.0914	0.0997	0.1077

Table 2-21: EU-27 Electricity Tariff, €/kWh

For *DER electricity prices* are subsidised and significantly higher, therefore EU countries implement a Renewable Energy Certificate System (RECS). The system[57] advocates a standard certificate as evidence of the production of a standard renewable energy quantity and provides a methodology which enables renewable energy trade. This enables a market for renewable energy to be created, so promoting the development of new renewable energy capacity in Europe. Price statistics can be found on the website and vary about *€0.3/kWh*.

2.4.4 Repair and maintenance costs

There is little maintenance schedules for transformers. It consists of annual checks for dust build-up, vermin infestation, and accident or lighting damage.
Repair costs are associated with the replacement and repair of components that have failed e.g. periodically filtering of the free-breathing transformer oil and exchanged because this degrades over time and loses its insulating qualities. Fire-extinguishing equipment must also be maintained.

It can be assumed that these repair and maintenance costs will not significantly change with increased efficiency.

[57] www.recs.org

2.4.5 Interest and inflation rate

The services of the European Commission proposed to use a 4 % discount rate (interest minus inflation).

2.4.6 Smaller industrial end user transformer prices

Smaller industrial end users might not procure transformers at the same price as DSO/TSOs or large industrial users. They might procure transformers trough a subcontractor as part of a turn key installation contract including: fuses, breakers, cables, distribution boxes, transformer, installation, etc.. Therefore they will pay a higher price, typically 10-30 %. For the impact please consult the transformer price sensitivity analysis in chapter 6.

CHAPTER 3 USER BEHAVIOUR

Scope:
This chapter explores the consumer behaviour and local infrastructure aspects for transformers and their influence on the energy and environmental performance of these devices.
Product-design may influence the consumer behaviour to some extent which consequently will influence the environmental impacts and the energy efficiency associated with the product during its use phase. Consumer behaviour has a significant direct effect on the use of transformers equipment during all phases of their life-cycle.
Analysing the consumer behaviour and real life situation in comparison with the standard test conditions will provide a more accurate picture of the real energy use.
This section aims to identify the user parameters and also the barriers to possible eco-design measures, due to social, cultural or infra-structural factors.

Summary:
The most important information contained in this chapter concerns the transformer load profiles because they have a significant influence on the real life efficiency of the transformer. The characteristic parameters are the Load Factor (ɑ) and the Load Form Factor (Kf) (see Table 3-1 below) that are defined for different user profiles.

<table>
<tr><th>Typical transformer</th><th>Load factors (ɑ)</th><th>Load form factors (Kf)</th><th>Power factor (Pf)</th><th>Load factors eq. flat($ɑ_e$)</th><th>Avail-ability factor (Af)</th><th>B/A TCO ratio ($ɑ_e^2$)</th><th>Aver-age Life-time</th></tr>
<tr><td>MV/LV distribution oil</td><td>0.15</td><td>1.073</td><td rowspan="6">0.9</td><td>0.18</td><td>1</td><td>0.0324</td><td>40</td></tr>
<tr><td>Industry oil</td><td>0.30</td><td>1.096</td><td>0.37</td><td>1</td><td>0.1369</td><td>25</td></tr>
<tr><td>Industry dry</td><td>0.30</td><td>1.096</td><td>0.37</td><td>1</td><td>0.1369</td><td>30</td></tr>
<tr><td>Power</td><td>0.20</td><td>1.08</td><td>0.24</td><td>1</td><td>0.0576</td><td>30</td></tr>
<tr><td>DER (liquid-immersed and dry-type)</td><td>0.25</td><td>1.50</td><td>0.42</td><td>1</td><td>0.1764</td><td>25</td></tr>
<tr><td>Separation/isolation</td><td>0.40</td><td>1.096</td><td>0.49</td><td>0.2</td><td>0.2401</td><td>10</td></tr>
</table>

Table 3-1: Summary of main user parameters for different types of transformers

The average technical life of a power or distribution transformer is 25 years or more. The end-user behaviour, e.g. regularly overloading of the transformer, has a significant impact on the transformer life time.

The End-of-Life behaviour is also an important issue taken into consideration in the environmental impact assessment in Task 4. Therefore, it has been reported that about 99% (in weight) of the transformers are recycled. This high recycling rate can be explained by the high residual value of the transformer scrap materials (e.g. steel, copper, aluminium, oil).

3.1 User Information and transformer procurement

Objectives:

The objective of section 3.1 is to investigate the influence of providing product information to the end-users and on the influence it can have on the environmental performance of the equipment, and on eco-practices in sustainable product use; and whether it could be useful to consider labelling or provision of other eco-information (e.g. ecological profile of the product). Barriers to the provision of such information and eco-design measures, due to social, cultural, and infrastructural factors will also be investigated.

3.1.1 Definition of type of users

These products are procured in a B2B market with technical and economic skilled end users.
In general, there are two types of users of transformers within the scope of this study:

1. *Utilities* that operate the electrical distribution or transmission grid, also called Transmission System Operators (*TSO*) or Distribution System Operators (*DSO*) (see also chapter 1).
2. *Owners* of *large industrial plants* or *large sites in the tertiary sector* (e.g. office building, hospital, shopping mall, ..);
3. *Owners of small industrial transformers, in some cases these transformers are part of a particular system or equipment.*

3.1.2 Method of providing product information

These products are procured in a business to business market with technical and economic skilled end users. Lack of user information can often be deducted to a lack in standards. A missing standard is frequently caused by a disagreement amongst manufacturers on test methods.

3.1.3 Influence and impact of product information

3.1.3.1 Lack of user acceptance for long pay back periods

Most end-users will assess their purchase and evaluate the available technology options and related energy (and cost) saving potentials for their specific situation. Loss evaluation is almost always undertaken, stating iron and copper loss values EUR/kW, calculated from period, interest and cost of electricity. Purchase decisions for transformers are often made on life cycle cost and payback considerations. Efficient transformers are often more expensive (see task 2) and purchasers need to take into account longer payback period.

Industry will not be able to replace their transformers if the pay-back time is >20 years. This is only feasible for utility transformers because they calculate the pay back on a very long period.
For smaller industrial transformers this might be even more the case, when transformers do not have significant annual operational hours.

Industry might also benefit from information on the residual value of the transformer after the depreciation time period (e.g. 10, 15, 20 years) due to the copper and steel scrap material price. A solution might be to provide information on the value of scrap material in relation to the product price.

DER investors have often very short payback time targets. It might be so that in essence, only DSOs and TSOs demonstrate overall life cycle optimisation targets when purchasing transformers.

3.1.3.2 Lack of information on energy efficiency of existing transformers in service

Furthermore, operators will often not substitute transformers before they fail. Although they may be aware of the losses, or maybe oversized older, less energy-efficient transformers, it is not foreseen realistic to change them. In many cases the losses of existing transformers are not exactly known, as they are not included on the transformer nameplate.
In order to avoid this situation in the future it could be recommended to include the load and no-load losses on the name plate, alternatively the classes as defined in EN 50464-1 for oil filled transformers.

Options are:
A. No information on transformer name plate;
B. Add the load and no-load losses on the name plate and specification sheet;
C. Add a load and no-load losses class indicator on the name plate and specification sheet (e.g. EN 50464-1);
D. Add a separate energy efficiency label similar to household appliances.

B is considered to be evident as routine tests are always made and figures are readily available at the time of delivery (comments stakeholder meeting, 06 July 2009).

Manufacturers are in favour to indicate option C, if the classes of efficiency of transformers are defined in a standard (T&D Europe, comment on stakeholder meeting 06 July 2009).

ERDF refer in its tender procedures to the standards (norm.edf.fr document HN 52-S-20), they also specify to that the EN 50464-1 load classes should be on the name plate.

3.1.3.3 Possible barrier by lack on information on dimensional an physical constraints

More efficient transformers tend to be bigger in size and heavier in weight. This could be of concern for retrofit applications, mining applications, telephone pole capacities, and other installations where transformers have to comply with dimensional or physical constraints. As approximately 80% of transformers sold are for replacement

installations (DOE, September 2007[58]), this issue of pre-existing space limit could cause problems.
There might be a need to timely inform the user on this increased need for installation space. However, stakeholders mention that space constraints are not seen as a reason to choose a noisier and less efficient transformer.

3.1.4 Procurement of transformers based on Total Cost of Ownership taking transformer losses into account by utilities

The first step in the procurement process is drafting the technical specifications, guarantees and schedules identifying the requirements and minimum standards that have to be met by the manufacturers. This sets out the contractual conditions which will be the basis of a contract between users and transformer manufacturers. To set up this list of technical specifications the EN 60076 can be used as a starting point or the list given in the J&P Transformer Book (Table 8.1 in the J&P Transformer Book[59]).
Next step is to assess the tenders and identifying the total cost of ownership of the transformers. This cost can be calculated by summarising the cost of the transformer and the costs of losses, using the formulas given in the HD 428 and HD 538 (SEEDT, June 2008[60]).

TCO= PP + A*Po + B*Pk

Where,

PP	=	purchase price of the transformer
A	=	cost of no-load losses per Watt
Po	=	rated no-load loss
B	=	cost of load losses per Watt
Pk	=	rated load loss

A and B values depend on the expected loading of the transformer and the energy prices. The cost parameters A and B take full network losses into account including cable losses. Moreover those cost parameters for load and no-load cost can also take into account that peak load electricity is more expensive. Usually these A and B figures are also part of the technical specification. The result of this procurement process should be the cheapest transformer, having the lowest total cost of ownership, taking into account the losses and optimised for a given application.

The TCO ratio B/A is related to the load parameters (Kf, PF, α, AF) used in this study and can be derived from formula 3.2 in section 3.2.1.1.3 in the assumption of similar electricity cost for load and no load losses.

$$\text{TCO } B/A = (\alpha \times Kf/PF)^2$$

TCO B/A ratios for typical use cases in this study are included in summary Table 3-1.

The SEEDT-reports proposes a methodology for determining the A and B factor for distribution transformers:

[58] Department of Energy (DOE), Technical support document: energy efficiency program for commercial and industrial equipment: electrical distribution, September 2007
[59] Martin J. Heathcote 'The J&P Transformer Book, A practical technology of the power transformer', Elsevier, 2007
[60] SEEDT report, 'Selecting energy efficient distribution transformers – a guide for achieving least-cost solutions' Project No. EIE/05/056/SI2.419632, June 2008, prepared for the Intelligent Energy Europe Programme by the Polish Copper Promotion Centre and European Copper Institute.

No-load loss capitalization – A:

$$A = \frac{(1+i)^n - 1}{i*(1+i)^n} * C_{kWh} * 8760$$

Load loss capitalization – B:

$$B = A * (\frac{I_l}{I_r})^2$$

Where,

i	=	interest rate (%/year)
n	=	lifetime (years)
C_{kWh}	=	kWh price (€/kWh)
8760	=	number of hours in a year (h/year)
I_l	=	loading current (A)
I_r	=	rated current (A)

The difficulty is to define the future loading profile and electricity costs and tariffs.

Furthermore some EU Member Statesincluded maximum load and no-load losses for distribution transformers (e.g. class CC') into their National Energy Efficiency Action Plan (NEEAP), in accordance with Directive 2006/32/EC on energy end-use efficiency and energy services (see §1.8.3). These NEEAPs describe the energy efficiency improvement measures and include efficiency requirements for local TSOs and NDOs, which can be transposed in local legislation.
Despite the fact that there are no mandatory minimum efficiency standards in Europe and the wide application of the total cost of ownership approach as explained above, there are some procurement procedures (internal standards of electricity distribution companies) which also include explicit minimum efficiency requirements for distribution transformers. Highly demanding are for example utilities in the Benelux, Germany, Austria, Switzerland and Scandinavia. Most of the electricity distribution companies in these countries buy transformers at AoBk (50464 standards). ERDF refer in its tender procedures to the standards (norm.edf.fr document HN 52-S-20), they also specify to that the minimum EN 50464-1 load classes.
Power transformers are nearly always based on public tenders that include the total cost of ownership approach.
Consumers of smaller industrial transformers most frequently do not mind transformer efficiency at all.

3.1.5 Procurement of smaller industrial transformers

Such transformers are often part of a system and the focus might be a certain design parameters such as high impedance/low saturation voltage possibly compromising the relevance of a strict loss efficiency focus.
It is uncommon to take energy efficiency into account for these transformers.

3.2 User behaviour in the use phase

The end-user behaviour has a significant impact on the transformer's overall environmental performance. This paragraph describes the most important functional

performance parameters of transformers which influence the energy efficiency and transformer application.
Furthermore best practices and maintenance practices to reduce failures and improve the overall performance of a transformer are discussed.

3.2.1 Real life efficiency

3.2.1.1 Transformer load profile

3.2.1.1.1 General introduction

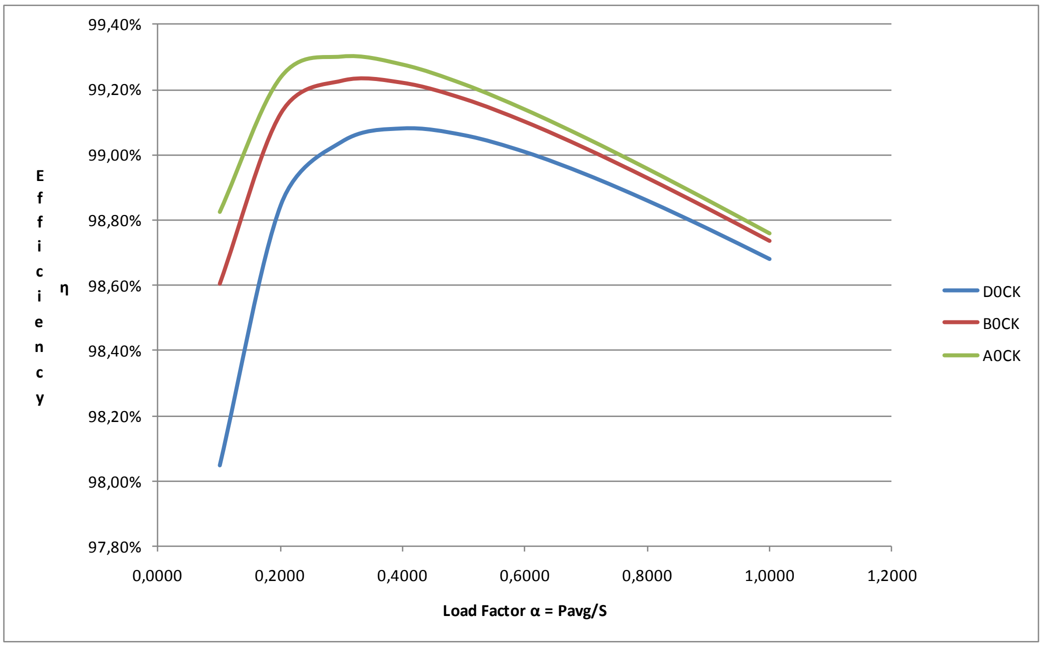
The key input for estimating the distribution of the transformer energy use in real life is the transformer load profile.
A load profile is a graph of the variation in the electrical load versus time. In an electricity distribution network, the load profile of electricity usage is important to the efficiency and reliability of the power transmission.
Correct sizing of a transformer is a non expensive tool for increasing the energy efficiency of the whole system. The sizing and modelling of transformers depends on the load profile. Distribution transformers for residential areas are often sized by the installed total power of the load, multiplied by a simultaneity factor.
Transformers need to be sized to cope with expected peak loads, rather than average loads. A transformer typically has a cyclic rating allowing for the variation in the load profile. This cyclic rating allows the transformer to be overloaded at peak times as long as there is a sufficient cooling down period at the lower point in the load profile.
For example, distribution transformers serving primarily residential loads regularly carry average loads that are only 15 percent to 20 percent of the transformer's rated capacity but also must be designed to support peak morning and evening loads. Because of the wide gap between peak and non-peak loads, and the relatively limited amount of time that the transformer is peak-loaded, average transformer load tends to be fairly low. In this case, total losses may be mainly attributed to core losses.
Larger distribution transformers, used more often in transforming power for commercial or industrial customers, tend to be loaded at higher average levels over the course of the year. Transformers that serve businesses operating from 9:00 am to 5:00 pm, for example, typically experience a consistent and relatively higher load throughout the day.
The factory specification of transformers thus depends on the characteristics of the load profile that the transformer is expected to be subjected to. The main characteristics are the average load form factor (see §3.2.1.1.4) and the load factor (see §3.2.1.1.5), which can all be calculated based on a given load profile.

3.2.1.1.2 Impact of load factor on transformer efficiency

As shown in Figure 3-1 , the load will affect the efficiency and also adversely affect the total life costs of the transformer. If the load factor ($\alpha = PAvg/S$) is below 15% then the overall energy-efficiency is also low. The highest efficiency (Pout/Pin) is usually achieved between 0.3 and 0.4. As peak load losses are economic more expensive distribution transformers are often designed to operate on left side compared to the top in Figure 3-1. The left side of the top also leaves some safety margin in case the energy consumption would increase over the transformer life time. Moreover transformers are sold in discrete values (250, 400, 630 kVA) will choose rather a higher rated transformer to be on the safe side. As a consequence a logic equivalent load factor ($\alpha = PAvg/S$) to operate a transformers is about 0.15-0.3.

It is important to recall from a design perspective that every transformer has its optimum efficiency at the point where the watts of no load losses are equal to the watts load losses. At that loading point, the transformer will be at its peak efficiency, the "apex" of its efficiency curve (Figure 3-1).
If that apex moves to a very low loading point – such as 15% loading, then the design software will create a design with a very large core cross sectional area and low magnetic flux. This will increase load losses (at the expense of no-load losses) and create a curve that is efficient at low loading points but which drops (significantly) in efficiency at high loading points.
Similarly, if the apex of the efficiency curve (where NLL=LL) occurs at a significantly high point – such as 85% of rated nameplate, then the transformer will have very poor performance at the lower loading points.

As the load profile varies according to customer type (typical examples include residential, commercial and industrial), this also means that there will be some variation in the energy efficiency between domestic, industrial and commercial applications because these have different load profiles. The load of industrial transformers is higher than that of utility transformers, so their energy efficiency will usually be higher.



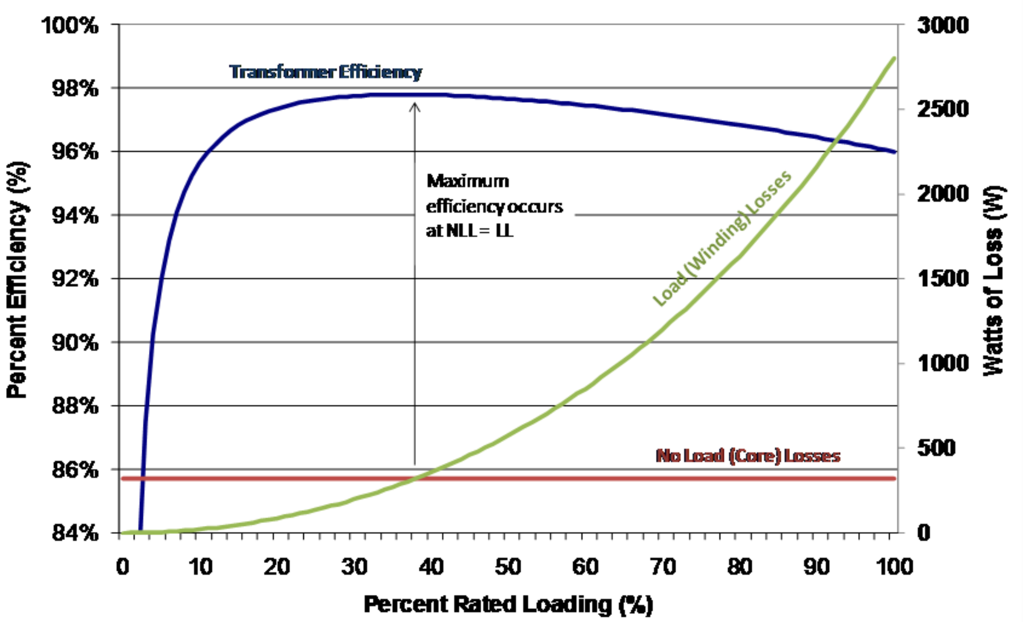


Figure 3-1: Transformer efficiency for different classes of 400 kVA oil immersed transformers (D0Ck, B0CK, A0Ck (top) and 75 kVA oil immersed transformer(bottom)

3.2.1.1.3 Impact of load profile on transformer energy losses

The energy used by distribution transformers is characterised by two types of losses (see chapter 1). The first type are no-load losses (Po), which arise primarily from the switching of the magnetic field in the transformer core material. No-load losses are roughly constant and exist whenever the transformer is connected. The second type of losses are load losses (Pk), which are also known as resistance or I^2R losses. Load losses vary with the load on the transformer and at any point in time are proportional to the load squared.

In order to easily calculate the annual energy loss of the transformer from data files with transformer loading it is convenient to switch to time independent parameters and use the so-called RMS load (Prms) or root-mean-square value of the power load load profile. The RMS load values can be easily computed from data files, e.g. from the Synthetic Load Profiles. In this case the annual energy loss (E(loss)) formula is:

$$Etr(y)\,[kWh] = AF \times ((Po[W] + Pk[W] \times (\alpha \times Kf/PF)^2 + Paux) \times 8760)/1000 \qquad \text{(formula 3.2)}$$

Where,

Etr(y) = the energy used by the distribution transformer per year [kWh],
Po = no-load losses at rated load (see chapter 1),
Pk = the load losses at rated load (see chapter 1),
Paux = the auxiliary losses (see chapter 1),
α = The load factor (Pavg/S) (as defined in this study see chapter 1)
Pavg = the average power of the load profile (see chapter 1),,
S = the rated power of the transformer (see chapter 1),
Kf = Load form factor (=Prms/Pavg) (see chapter 1)
Prms = the root mean squared value of the power of the load profile,
AF= Availability Factor (see chapter 1),
PF = the power factor of the load serve by the transformer (see chapter 1).

Because the load profiles are not always known some stakeholders use prediction formulas based on the maximum transformer power (Pmax)(Scandinavian approach):

$$Etr(y)\,[kWh] = (P0 + a(Loss) \times Pk \times (Pmax/S/PF)^2) \times 8760 \qquad \text{(formula 3.3)}$$

Where,

Etr(y) = the energy used by the distribution transformer per year [kWh],
a = Pavg/Pmax being an utility load factor utility not te be confused with α = The load factor (Pavg/S)for transformers as defined in chapter 1 ,
$a(Loss) = (5a^2-a^3)/4$,
Po = no-load losses at rated load (see chapter 1),
Pk = the load losses at rated load (see chapter 1)
Pmax= is the maximum projected transformer load,
PF = the power factor of the load served by the transformer (see chapter 1).

Other utilities (France, SEEDT[61]) often use a method based on equivalent time of peak loss for specifying and evaluating distribution transformer losses:

$$Etr(y)\,[kWh] = AF \times (Po + Pk \times \tau/8760 \times B_S^{\,2}) \qquad \text{(formula 3.4)}$$

Where,

E(loss)(t) = the energy used by the distribution transformer at time t [kW],
Po = no-load losses at rated load (see chapter 1) [kW],,
Pk = the load losses at rated load (see chapter 1) [kW],,
B_S = the assumed equivalent peak load of a transformer [ratio],

[61] SEEDT report, 'Selecting energy efficient distribution transformers – a guide for achieving least-cost solutions' Project No. EIE/05/056/SI2.419632, June 2008, prepared for the Intelligent Energy Europe Programme by the Polish Copper Promotion Centre and European Copper Institute.

AF= Availability Factor (see chapter 1)
T = equivalent time duration of the peak loss (h),

3.2.1.1.4 Load form factor (Kf= Prms/Pavg)

Load form factor for distribution and industry transformers:

In the free electricity market the knowledge of the load profile of a customer is used by DSO to calculate the rates for electricity retailers because electricity rates vary with time.
Metering energy consumption in function of time is too complex when no automatic meter reading is available, hence distribution companies use so-called Synthetic Load Profiles. Load profiles are commonly used in electrical distribution grids because they can be determined by direct metering. However on smaller distribution transformers (< 100 kVA) this is not routinely done. Therefore, for these transformers, suppliers implement a method that gives a sufficiently accurate picture of hourly consumption of groups of customers without appropriate meters. These costumer groups –e.g. industrial, non-industrial– are allocated to standardised load profiles or synthetic load profiles. These synthetic load profiles (SLP) are based on historical data and take into account the most important variables which determine the consumption, e.g. year calendar (weekdays, weekends, holidays) and seasonal factors (temperature, sunrise).

For example Germany and Belgium use these synthetic load profiles in order to take small customers' load behaviour into consideration:

- Synergrid, the Belgian federation for electricity and gas distributors, determines these synthetic load profiles for the residential consumers and the non-residential with < 56 kVA and with 56-100 kVA. An example of the Belgian synthetic load profile for the non-residential sector > 56-100 kVA for January 2009 is given in Figure 3-2. Without taking seasonal changes into account (Figure X) the Ppeak/Pmin is about a factor 2.5, taking seasonal changes into account this values easily rises until a factor 3.

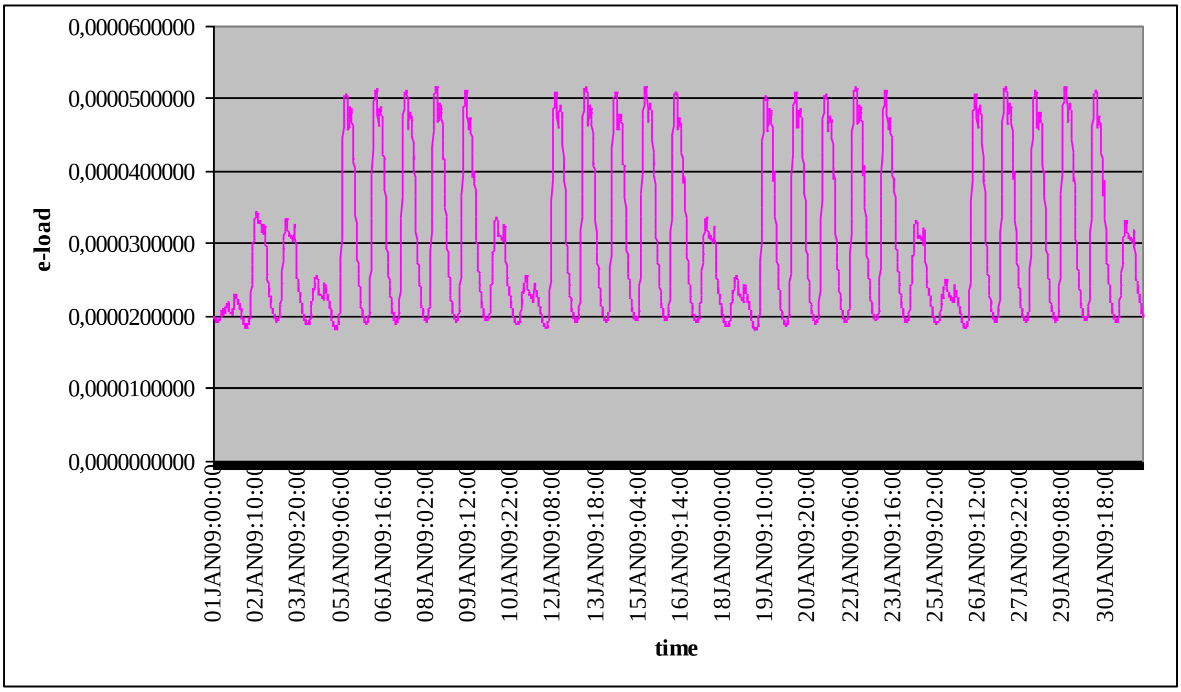


Figure 3-2: Synthetic load profile for the non-residential sector > 56-100 kVA for the month January 2009, electricity load (per unit) versus day of the month (date: hour)(www.synergrid.com)

- In German electricity organisation, VDEW[62], determined synthetic load profiles for households, industry and agriculture. An example of the SLP for the industry is given in Figure 3-3. This also shows that the maximum power compated to the minimum power is a factor 4, leaving no option to operate a transformer at a load factor (Pavg/S) of about 0.5.

[62] VDEW is now being replaced by BDEW (www.bdew.de)

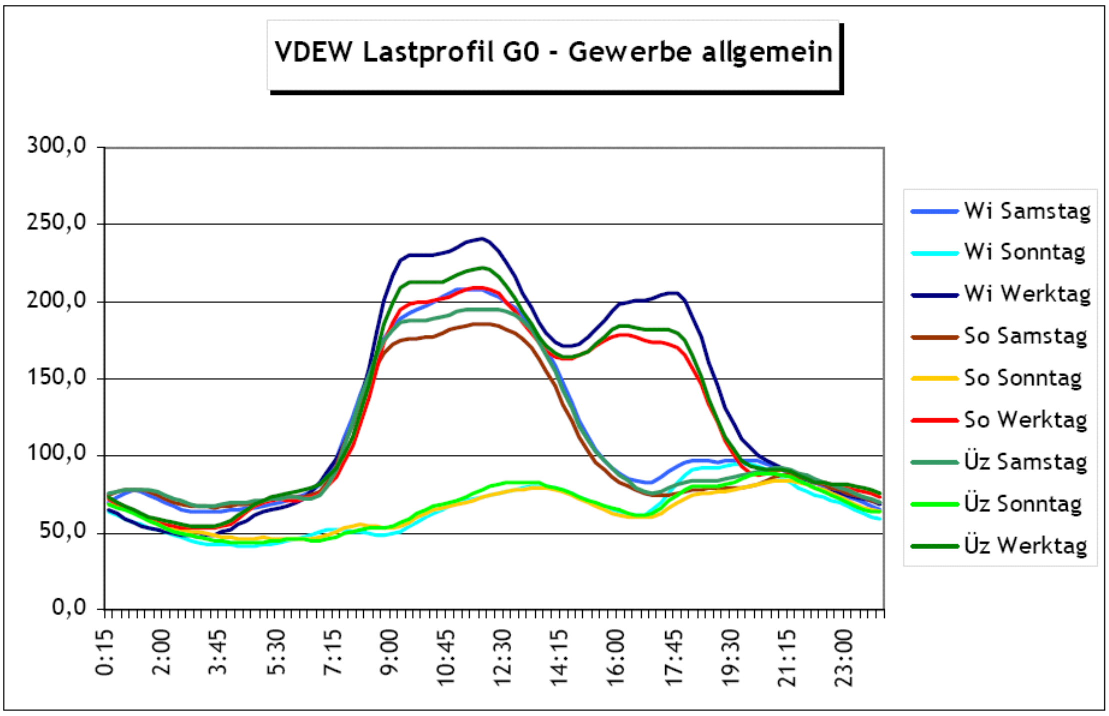


Figure 3-3: Synthetic load profile for the industry for one specific day (Kalab[63]), consumption (per unit) versus time of the day (h)

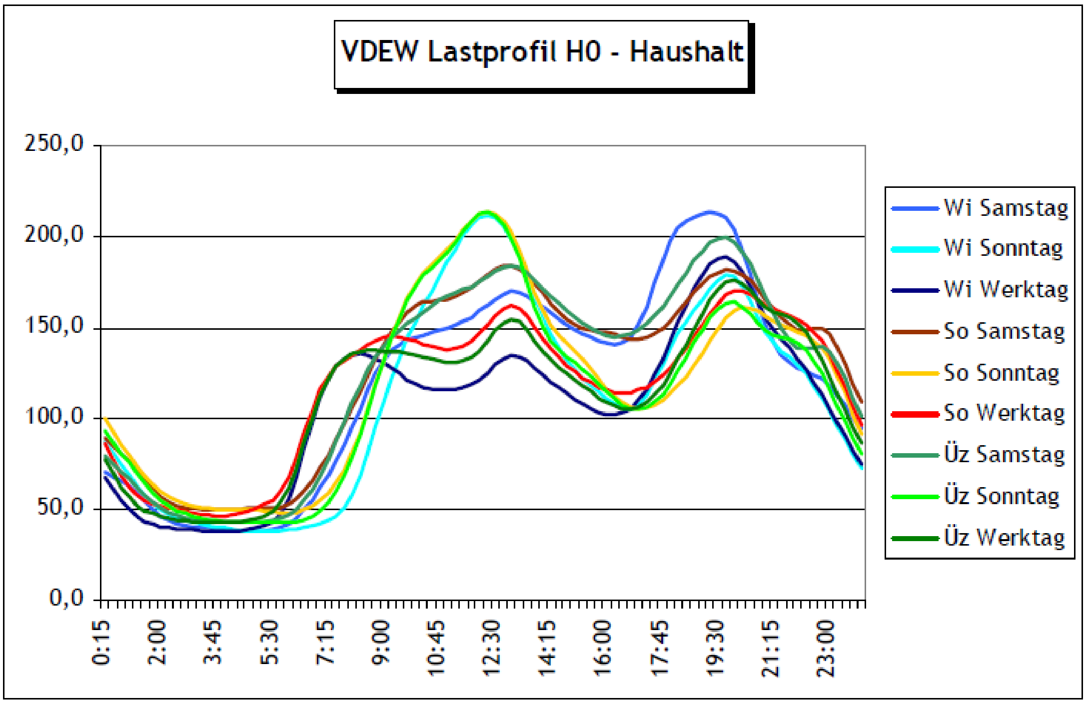


Figure 3-4: Synthetic load profile(per unit) for households for one specific day (Kalab[64]), consumption versus time of the day

[63] Kalab Otto, Standardisierte Lastprofiele

These domestic load profiles are very similar all over Europe, more details on the origin of these load profiles (lighting, refrigerator, cooking, ..) can be found in the REMODECE study[65].

SEEDT&ERDF:

Load form factor for DER transformers (DER[66]):

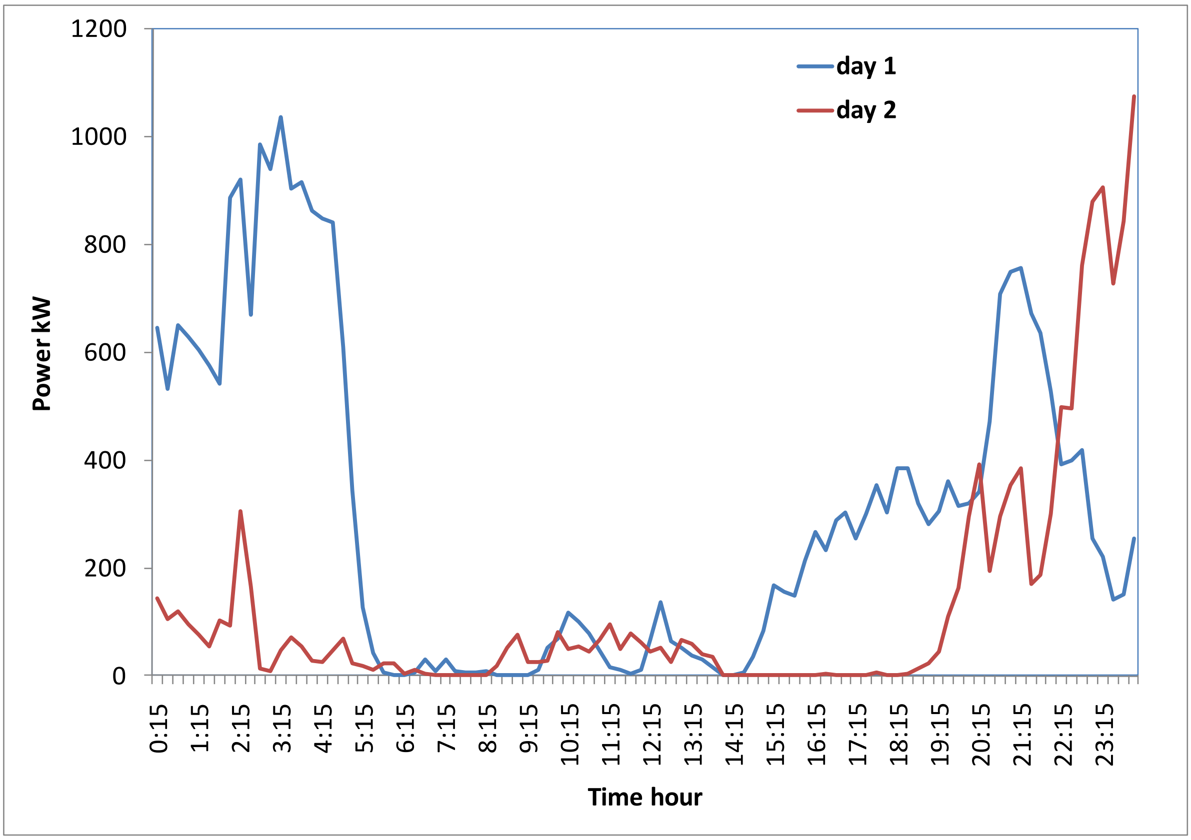


Figure 3-5: Metered data from an inland wind turbine (1 MW) (resulting use factors: α=0.21, Kf=1.6, AF=1 or α=0.25, Kf=1.5, AF=0.85)

For distributed energy systems based on wind energy or solar energy no such synthetic load profiles are used, they can be deducted from metered data (Figure 3-5). A load form factor of 1.60 was calculated from this data (AF =1, α=0.21). When the transformer is connected at periods that there is no wind this leads to load form factor of 1.50 (AF=0.85, α =0.25). This means that the energy produced by wind varies strongly over time. The data was obtained by processing of metered data, for confidentiality reasons the brand name of the turbine and location cannot be disclosed.).

Load form factor for power transformers:

This was assumed to be in between distribution and industry, because both are mixed at this level in the grid.

[64] Kalab Otto, Standardisierte Lastprofiele
[65] REMODECE project report, 'Residential Monitoring to Decrease Energy Use and Carbon Emissions in Europe', November 2008, IEEA PROGRAMME.
[66] Distributed Energy Resource

Conclusion on load form factors:

For industry it proposed to use the VDEW G0 profile and for distribution VDEW H0 is used (see Table 3-2). As can be seen those values do not vary significantly and as a consequence they do not have a strong impact on the result.

Application	Kf (= Prms/Pavg)	Profile used
Distribution	1.073	VDEW G0
Industry	1.096	VDEW H0
Power	1.08	Assumption
DER (wind)	1.60 (AF =1, ɑ =0.21) 1.50 (ɑ =1.25)	Experimental data (Vito)
Small transformers	1.096	VDEW H0

Table 3-2: Load form factors (Kf) to be used in this study

3.2.1.1.5 Load Factor (ɑ = Pavg/S)

This section describes the used Load factors (ɑ) for distribution and industry transformers as defined in chapter 1 (=Pavg/S).
Note: The load factor ɑ as defined in chapter 1 for transformers should not be confused with Pavg/Pmax (= LFu) as frequently used by utilities or in other literature, this 'utility load factor' is of course higher.

Based on the information given in Task 2 (installed capacity & energy use data in section 2.2.6.4) and the definition of the load factor given above, the load factors for the transformers considered in this study can be calculated, see below:

	Annual demand TWh	Installed MVA	Hours per year	Average load factor (ɑ)
Household/other utiliy/transport (assumed mainly DSO clients)	1553	893 913	8 760	0.2
Industry (assumed mainly TSO clients)	1136	461 096	8 760	0.28

Calculation: (annual demand in MWh/hours per year)/ (installed MVA)

Table 3-3: Calculation of the load factors for utility and industrial distribution transformers based on the annual electricity demand per sector and the maximum capacity

The data in Table 3-3 gives an idea of the relative low load factors, however the average load factor of 0.2 can only partially be linked to a so-called 'distribution transformer' in Table 3-5. So called other utility clients could be SMEs or office buildings which are in this study considered as 'industrial transformers'. Therefore the average load factor of 0.2 in Table 3-3 reflects a value in between a typical 'distribution transformer' 0.15 in Table 3-5 and an 'industrial transformer' of 0.30.

To verify the calculated load factors, literature regarding the average load factor on the transformer (commercial, industrial, residential) is examined:

- In 1999, the Northeast Energy Efficiency Partnership (NEEP)[61] contracted the Cadmus Group to measure transformer loading and harmonic levels in a variety of commercial and industrial installations. In the 89 buildings that were analysed (comprised of a collection of universities, health care facilities, manufacturing facilities, office buildings and retail facilities) the average RMS loading factor was found to be 15.9% (varying between 14.1% to 17.6%).
- Office lighting[67] have typical annual operating hours ranging from 2000-2500 hours per year which should be equivalent to a load factor (Pavg/S) = 2250h/8760h = 26 %. However there is always some extra marging for extra loads (elevator, more ICT,..) and at the time of purchase one would allways rather select one step larger (e.g. 400 kVA instead of 250 kVA), that might explain above value of 15.9 %. Please note that in our approach also the power factor will be added afterwards and the designers do this as well.

- A study from the Leonardo energy organisation[68] states a load factor of 15-20% for transformers used to serve residential customers. Commercial customers use typically 30-50% of the transformer capacity. Other sources report for utility transformers average loading levels of about 25-30% are reported (TR Blackburn, October 2007[69]).

- The SEEDT[70] IEE Europe study (2008) used an average load of 18.86 % (including the power factor), which is very close to this study (Table 3-1 αe = 0.18).

- According to T&B Consultancy (stakeholder meeting comments: 'Higher utilisation factors (e.g. sweating the assets) increases the costs of lost energy, lower losses can be obtained by operating at lower utilisation or transformers with larger than necessary conductors'. Apparently low load factors and oversizing transformers might be a strategy to reduce load losses. For example, Pavg = 200 kW and α =0.50 with 400 kVA Ck(4600 W) results in 1150 W load loss while 630 kVA Ck (5400 W) and α=0.32 (200/630) results in only 540 W. As a conclusion oversizing is a good strategy to reduce losses, moreover it makes the grid more reliable. To be compared no-load losses for 400 kVA B0 are 540 W and 630 kVA B0 are 730 W. In general load losses are more expensive because they coincide with peak losses.

- Note: The DOE (see chapter 1) assumes an average 50 % transformer for transformer MEPS, this is not in line with the previous findings. Nevertheless, transformer standards and ratings are different in the US so any comparison is difficult.

- France (ERDF) and Ireland (ESB) have provided precise data on the transformer stock and annual distributed electricity over these transformers.

- France (ERDF communication) have reported 740.000 transformers (2007) with an average rating of 190 kVA. In 2007 those transformers delivered 188 TWh to

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[67] Preparatory Studies for Eco-design Requirements of EuPs: 'Final report lot 8 on office lighting' (see www.eup4light.net)
[68] Leonardo Energy Transformers, 'Potential for global energy savings from high efficiency distribution transformers', February 2005
[69] Leonardo Energy Transformers, 'Potential for global energy savings from high efficiency distribution transformers', February 2005
[70] SEEDT 'Selecting Energy Efficient Distribution Transformers-A Guide for Achieving Least-Cost Solutions', June 2008.

33.6 million end users[71] or 21.5 GW on average compared to 140.6 GVA transformers installed. This is equivalent to 0.15 or the result included in Table 3-5.

- Ireland (ESB Networks) have reported 229499 transformers (2006) with an average rating of 55 kVA. In 2006 those transformers delivered 16.6 TWh to 2 million end users[72] or 1.89 GW on average compared to 12.56 GVA transformers installed. This is also equivalent to 0.15 or or the result included in Table 3-5.

- A low load factor for residential such not be a surprise when looking to potential fluctuation in loading compared to the average power. The average domestic power in EU27 is only estimated at 413 Watt from 795 Twh used by 210.5 M households (Table 2-17, 2-15). This average power is much lower compared to the power comsumption of many home appliances, e.g.: cooking 500-9000 Watt, lighting 60-1000 Watt, TV 50-500 Watt, ICT 50-300 Watt, washing&drying 500-2000 Watt, ... Also the power factor should not be overlooked (see 3.2.1.2). Moreover new residential developments would rather upscale because more types of appliances are used, heating and cooling might rely more on heat pumps and electrical vehicles might be used. This is also reflected in the main fuse in households: 1x40 A(typically B), 1x90A(typically F), 3x63A (typically D) corresponding to residential power limits ranging from 10 kVA to 43 kVA. When a group of households connected to a transformer simulatiously cooks, washes, lights its house, watches TV and uses some multimedia equipment clearly the average could be far above 413 Watt (e.g. 3000 Watt). Such an event can occur: e.g. match of the national football team. Therefore transformers are dimensioned at such events and load factors (Pavg/S) are correspondingly low (e.g. x0.15). See also how transformer rating is typically at its installation in section 2.2.2.1.

- Industrial transformers have higher average loads than utility transformers and so the energy savings are potentially higher. On the negative side, they do not always have the same quality of maintenance procedures such as those used by utilities. Also, in the industry, overloading is more likely to occur with the attendant reduction of efficiency that the higher load losses cause.

- An overview of the RMS load factors (= α x Kf) for distribution transformers in different sectors is given in the table below. These load factors are based on a questionnaire from 290 users in Japan (Japan Electrical Manufacturers Association). In order to obtain the load factor (α) the RMS load factor needs to be divided by the form factor (Kf), which is about 1.1.

[71] Résultats Techniques du Secteur Electrique en France (2007), http://www.rte-france.com/uploads/media/pdf_zip/publications-annuelles/rtse_2007.pdf

[72] Key Statistics 2006 (ESB networks).

Sector	Daytime	Night time	Day average
Industry			
Electric	0.50	0.36	0.43
Food	0.47	0.32	0.41
Metal	0.42	0.31	0.37
Chemical	0.48	0.26	0.38
Machinery	0.40	0.15	0.30
Fabrication	0.56	0.58	0.57
Pulp	0.35	0.35	0.35
Transport	0.25	0.00	0.18
Other	0.50	0.27	0.40
Services			
Offices	0.25	0.06	0.18
Stores	0.61	0.05	0.43
Public sector			
Hospitals	0.30	0.09	0.22
Libraries	0.23	0.05	0.17
Rail road	0.20	0.14	0.17
Government	0.40	0.10	0.29
Other	0.37	0.34	0.36

Table 3-4: Overview of the RMS load factors (α x Kf) in different sectors (Leonardo energy, February 2005[68])

The relative low load factors found in distribution might be explained by the need for redundancy and reliability, i.e.: the low acceptance for failures due to overload, the use of circuit breakers in industry to limit overload conditions, the use of fuses in residential distribution to limit overload, grid redundancy to cope with cable failures, redundant transformers to cope with transformer failures, fear for high peak loads due to simultaneous switching of loads, over sizing due to stepwise product range (250 kVA > 400 kVA) and over sizing to anticipate on a growing demand for electricity use,

Load factors for DER transformers

KEMA T&D Consulting [73] reports a load factor of 0.30 for wind turbine transformers, based on 750 kW wind turbine with a production 2550 MWh per year (38.8% load) and a transformer of 1000 kVA. Please note that this is higher compared to experimental data obtained in Figure 3-5 (LF=0.21&Kf=1.6&AF=1, LF=0.25&Kf=1.5&AF=0.85).

Load factors for power transformers

For power transformers, no robust data on the load factors was found in available literature. Based on the information given in Task 2 and the information given by the sector organisation T&D Europe, the load factor for the power transformers is set at 0.20. This figure can be compared with the power trafo's2005 stock: 64000x100 MVA(Chapter 2) or 7500 GVA (ENTSOE) and the total energy end use demand in Eurostat (2005) of 2763 TWh which is average 315 GW (340GW) or about 5 % of installed capacity only. The higher assumed load factor of 0.2 can be explained by the fact that the energy in the grid needs to be transformed several times, in this case about a factor 4.

[73] KEMA T&D Consulting, Cost savings by low-loss distribution transformers: the influence of fluctuating loads and energy price on the economic optimum, September 2003

An explanation for this relatively low load factor for substations power transformers can be found on the high level of redundancy that is often incorporated in the electrical grid topology. A standard MV cluster in a dense populated area often uses a a linear or mixed (linear and star) "double derivation" topology [74]. In the 'double derivation' topology substations are connected to 2 cables and often use two transformers: one of them acts as "service cable" (breaker on) and the other one acts as "backup cable" (breaker off). For example Portugal has 368 substations feeding the MV grid with in total 654 power transformers installed with 12971 MVA transformation power [75], a similar situation is in many European countries.
An explanation for the relative low load factor for generator step up power transformers can be found in the fact that many power stations are only operational during peak demand and that those electric power generator plants have also redundant transformers.
Conclusion on load factors:

The calculated load factors seem to be on the lower side of the ranges found in the literature or indicated by the sector organisations. Based on the available literature and information, an average estimation for the considered transformers in this study is made to use in further evaluations, see Table 3-5 and minimum and maximum values are added that will be used in the later sensitivity analysis in chapter 7.

Application	**α (Pavg/S) Typ.**	**α(Pavg/S) Min.**	**α(Pavg/S) Max.**
distribution	0.15	0.10	0.25
industry	0.30	0.10	0.60
power	0.20	0.20	0.50
DER (wind)	0.25	0.20	0.30
small industry	0.40	0.10	0.60

Table 3-5: Load factors (α) to be used in this study

3.2.1.2 Power factor

The power factor is the real power used by the load divided by the apparent power required by the load conditions, and is a number between 0 and 1. The real power is the time average of the instantaneous product of the voltage and current. The apparent power is the product of the root mean square (RMS) voltage and the RMS current.

In an electric power system, for the same amount of useful power transferred, a load with a low power factor draws more current than a load with a high power factor. For example, if the load power factor were as low as 0.7, the apparent power would be 1.4 times the real power used by the load. Line current in the circuit would also be 1.4 times the current required at 1.0 power factor, so the losses in the circuit would be doubled (since they are proportional to the square of the current).
A high power factor is thus generally desirable in a transmission system to reduce transmission losses, and improve voltage regulation at the load. Typically domestic loads have power factors around 1, while industrial load will have lower power factors.

In France (ERDF communication) a power factor of 0.8 is used to procure and dimension transformers.

[74] OPERA FP 7 project: 'D13: Report on the requirements and specifications for the integrated communication systems: PLC MV-LAN and PLC MV-PLC LV'
[75] OPERA FP 7 project: 'D13: Report on the requirements and specifications for the integrated communication systems: PLC MV-LAN and PLC MV-PLC LV'

Note: in southern regions peak loads could be caused by air conditioners who are could have a poor power factors.

Synergrid [76] in Belgium assumes a power factor (PF) of 0.95, based on its experience.

Conclusion:
It is proposed to use PF = 0.9.

3.2.1.3 Availability factor

The availability factor (AF) indicates the proportion of time that a transformer is predicted to be energised. This is estimated to be 1, although for wind turbines or solar power plants this might be lower due to the non-constant wind availability.
Solar power plants transformers can be disconnected at night to reduce the transformer no-load losses (P0), resulting in an availability factor (AF) of 0.5.

The availability factor(AF) interferes with the load factor (LF) and load form factor (Kf). Figure 3-5 contains metered data from an inland wind 1 MW wind turbine. When the transformer is disconnected every time there is no wind this results in: LF=0.25, Kf=1. And AF=0.85. When the transformer is always energized (AF =1) this results in: LF=0.21 and Kf=1.6.

For the smaller industrial transformers it is unlikely that they are under continuous operation. They could be linked to the typical annual operational hours in industry or the service sector (2250 h/y), nevertheless a big spread is possible. Some industry equipment might also be operated partially (e.g. welding, industrial batch processes, seasonal processes, ..). The smaller transformers are also installed in the LV circuit and can therefore easily be switched off. For this reason smaller transformers also try to avoid high inrush magnetisation currents.

The proposed Availability Factors for this study are given in the table below.

Application	**AF (typ.)**	**AF (min.)**	**AF (max.)**
distribution	1	1	1
industry	1	1	1
power	1	1	1
DER (wind)	1 (LF=0.21, Kf=1.6)	0.85 (LF=0.25, Kf=1.5)	1
small industry	0.25	0.12	1

Table 3-6: Proposed Availability Factors for this study

3.2.1.4 Summary on loading profile parameters

Table 3-7 contains a summary of loading profile parameters.
For reasons of comparison a new equivalent load factor (αe) is introduced defined as the equivalent load factor (Pavg/S) for a transformer in the assumption of a flat load profile. Hence it is an 'equivalent load factor' with a 'flat profile' equivalent to Kf =1 and PF = 1.
Definition of equivalent load factor (αe):

[76] Synergrid, Raming van de verliezen in de distributienetten, August 2003

ɑe = ɑ x Kf / PF

Typical transformer	**Load factors (ɑ)**	**Load form factors (Kf)**	**Power factor (Pf)**	**Load factors eq. flat(a_e)**	**Availability factor (Af)**	**B/A TCO ratio (a_e^2)**	**Average Lifetime**
MV/LV distribution oil	0.15	1.073		0.18	1	0.0324	40
Industry oil	0.30	1.096		0.37	1	0.1369	25
Industry dry	0.30	1.096		0.37	1	0.1369	30
Power	0.20	1.08	0.9	0.24	1	0.0576	30
DER (liquid-immersed and dry-type)	0.25	1.50		0.42	1	0.1764	25
Separation/isolation	0.40	1.096		0.49	0.2	0.2401	10

Table 3-7 Summary of load profile parameters

3.2.1.5 Impact of harmonics

Almost all industries have non-linear loads. Non-linear loads generate high levels of higher frequency components in the load current (harmonics). Typical non-linear loads include:

- computers
- UPS systems
- variable speed drives
- inverters e.g. to allow the connection of photovoltaic and wind generators to the distribution grid system.

The extensive use of these electronic units causes increasing problems for distribution transformers:

- Higher frequency components in the load current (harmonics) cause extra losses because harmonics do not fully penetrate the conductor. They travel on the outer edge of the conductor. This is called skin effect. When skin effect occurs, the effective cross sectional area of the conductor decreases; increasing the resistance and the I^2R losses, which in turn heats up the conductors and anything connected to them (KEMA, May 2002)[77].

[77] KEMA, Energy saving in industrial distribution transformers, May 2002

- The harmonics in the load current will also increase losses in the transformers by generating eddy currents in the windings, which cause increased heating in the windings. These eddy currents in the windings represent 5% of the load loss. These losses are proportional to the square of the frequency. If the load current contained 20% fifth harmonic, the eddy current loss due to the harmonic current component would be 5 x 5 x 0.2 x 0.2 multiplied by the eddy current loss at the fundamental frequency. Consequently, the load losses in a transformer supplying non-linear loads can easily be twice the rated losses.
- The harmonics on the voltage will lead to increased core loss (no-load losses) due to higher frequency magnetic field components generated in the cores (SEEDT, 2008[78]).

To deal with these harmonics a few options are possible (LPQI, March 2009[79]):

- For existing transformers: de-rating of the transformer so that the total loss on harmonic load does not exceed the fundamental design loss. To estimate how much a transformer should be de-rated, the de-rating factor (known as factor K method, used in Europe)) may be calculated according to formula in HD 538.3.S1:

$$K = \left[1 + \frac{e}{1+e}\left(\frac{Ih}{I}\right)^2 \sum_{n=2}^{n=N}\left(n^q\left(\frac{In}{I1}\right)^2\right)\right]^{0.5}$$

with

e = eddy current loss at the fundamental frequency divided by the loss due to a DC current equal to the RMS value of the sinusoidal current, both at reference temperature.

N = harmonic order

I = RMS value of the sinusoidal current including all harmonics given by

$$I = \left(\sum_{n=1}^{n=N} (In)^2\right)^{0.5} = I1\left[\sum_{n=1}^{n=N}\left(\frac{In}{I1}\right)^2\right]^{0.5}$$

In = magnitude of the n-harmonic

I1 = magnitude of fundamental current

Q = exponential constant that is dependent on the type of winding and frequency. Typical values are 1.7 for transformers with round rectangular cross-section conductors in both windings and 1.5 for those with foil low voltage windings

- For new transformers: special design of transformers rated for non-sinusoidal load currents. The increase in eddy current loss is calculated and the transformer will be designed so that it can cope with these extra losses. These transformers are sold as 'K rated' transformers. The K-factor is estimated using the following equation:

$$K = \sum_{n=1}^{n=n\max} In^2 n^2$$

[78] Strategies for development and diffusion of Energy Efficient Distribution Transformers (SEEDT), Selecting Energy Efficient Distribution Transformers, A Guide for Achieving Least-Cost Solutions, Intelligent Energy for Europe, 2008

[79] Leonardo Power Quality Initiative (LPQI), Harmonics: selection and rating of transformers, March 2009

A pure linear load, one that draws sinusoidal currents, will have a K factor of 1. A higher K factor indicates that the eddy current loss in the transformer will be K times the value at the fundamental frequency. K rated transformers are thus designed to have very low eddy current loss at fundamental frequency.

– Use energy efficient transformers to minimise losses with non-linear loads.

The latter option is obviously the best approach.

Conclusion:
It is proposed to not take this effect into account by a lack of data and it will not benefit inefficient transformers in normal use.

3.2.1.6 Transformer ambient temperature

The copper and aluminium resistance increases with temperature, hence the load losses can increase or decrease with temperature.

Transformer manufacturers often specify load losses at 75°C and at 120 °C, e.g. Pk 75 is 8800 Watt and Pk 120 is 10000 Watt (i.e. 14% increase with 45 °C temperature increase).

Conclusion:
It is proposed not to take this effect into account because its impact is relative to the chosen reference; hence it will not influence the outcome

3.2.2 Best practice in sustainable product use

The lifetime of a transformer is mainly determined by the lifetime of the insulation of the transformer. The insulation mainly has an organic nature; being composed of mineral oil, impregnated paper, cellulose materials, etc. The stability of such materials is very dependent on the operational temperature. The usual rule of thumb is that continuous operation above the rated temperature by only 6°C will halve the lifetime of the insulation (T.R. Blackburn, October 2007[80]).

The end-user behaviour, e.g. regularly overloading of the transformer, has a significant impact on the transformer life time. Therefore, a number of manufacturers give recommendations for smart use of such transformers and "energy-saving tips" to end-users. Such strategies aim at reducing the losses and improving overall performance of transformers which can be achieved through better monitoring and maintenance practices.

3.2.3 Repair and maintenance practice (frequency of repair and failure, spare parts, transportation and other impact parameters):

Transformers require less care and attention than almost any other kind of electrical apparatus. However, transformers not only represent considerable investment but they are essential in maintaining the continuity of electric service. Failure of a transformer

[80] T.R. Blackburn, 'Technical Report - Distribution Transformers: Proposal to Increase MEPS Levels, Prepared for Equipment Energy Efficiency Program', October 2007

can cause a great deal of consequential damage to associated apparatus. Therefore, it is important that transformers be kept in serviceable condition[81].
Although transformers are highly reliable and efficient devices, routine inspections performed by the equipment owner can identify potential problems in their early stages. Most transformers are equipped with basic indicating devices that, when routinely monitored and recorded, will indicate a change from normal operation conditions.

For power transformers the following data was reported[82].:

source	Occurrence per year
Major power transformer failure	0,00569
Minor power transformer failure	0,01138
Maintenance interval (if needed, e.g. oil)	0,1
Inspection interval (recommended)	0,5

Table 3-8: Typical repair and maintenance intervals for power transformers

3.2.4 Economic product life (= actual time to disposal):

Lifetime is a crucial component of the life cycle cost (LCC) calculation. Transformers are durable and have long working lives. For financial purposes, the amortisation period for an investment in a transformer is often set at 20 years.

The average technical life of a transformer is 30 years or more; more than 10% of the European transformer fleet is 40 years old or more. This 10% of the transformer fleet contributes more than 20% of the total no-load losses and more than 15% of load losses in European distribution companies.
The minimum reasonable transformer lifetime in LCC calculations could be 20 years and arguments mentioned above indicate that applying 30 years lifetime in industry and commerce, and 40 years lifetime in electricity distribution companies can be justified as well (SEEDT, 2008[78]). Dry type transformers in industry are more expensive and therefore a 5 years higher average economic life time was assumed. Minimum and maximum life times will be used for the sensitivity analysis in chapter 7 while the average is used for the stock model in chapter 2 and the base cases in chapter 4.
According to Eurelectric comments the life time of power transformers in Transmission Systems (TSO) is lower compared to distribution transformers, therefore 30 years will be adopted. The values used in this study are summarized Table 3-9.

[81] I.Jeromin, 'Life Cycle Cost Analysis of transmission and distribution systems', IEEE Bucharest Power Tech Conference, 2009
[82] I.Jeromin, 'Life Cycle Cost Analysis of transmission and distribution systems', IEEE Bucharest Power Tech Conference, 2009

Application	**Life time (y. typ.)**	**Life time (y. min.)**	**Life time (y.max.)**
distribution	40	30	50
Industry oil	25	20	40
Industry dry	30	20	35
power	30	25	35
DER (wind)	25	20	30
small industry	10	10	20

Table 3-9 Transformer life times used in this study

3.3 End-of-Life behaviour

Two main end of life options are available, which always entail considerable expenditure by the owner (The Hartford Steam Boiler Inspection and Insurance Company, October 2002[83]).

1. Repair: Repair costs can be high essentially because of design constraints, and the effects of the unknown. The most extensive (and expensive) repair is a complete *rewind* of the transformer coils. However, in the decision to rewind versus replace old transformers, it is important to include the costs of transformer losses. The cost of core and copper losses for a 1950's transformer may be twice that of a new transformer. Customers thus decide to replace the transformer (instead of rewinding it) because the reduction in core losses could economically justify it. Another major repair option is *reblocking and reclamping* the transformer coils. Over time, thermal and mechanical cycling can result in a gradual decrease in the vertical clamping pressure (axial) on the coils. These forces can decay at a different rate for different windings or for different layers of the same winding. At some point, the coil clamping may fall below the level required to hold the coils stable during through-fault events. The transformer is typically reclamped to the original values specified by the manufacturer. However, if there is any possibility of internal insulation damage or conductor "tilting", due to previous faults, the reclamping process should be avoided. Reclamping, in this case, may exacerbate the pre-existing condition, and accelerate a failure. Other options include the *repair or replacement of ancillary equipment*, such as surge arresters, bushings, fans, pumps, radiators, pressure relief devices, oil and winding temperature gauges, liquid level gauges, fault-pressure relays, gas detector relays, load tap changer maintenance /upgrade (contacts), and oil dry out/reclamation.
2. Replacement: Replacement with a new unit provides the benefits of an improved, more energy efficient design but is very expensive. In Europe dismantling and incineration is mostly used, with the recovery/recycling of the metallic components (copper, steel, aluminium). The contained oil will be incinerated.
   Furthermore, delivery times are also decreasing and are beginning to approach repair spans. Some utilities used to replace a transformer when the associated load reached 100% of transformer nameplate capacity. Some utilities also used to replace a transformer when its calendar age reached an arbitrary value of 30 to 35 years. Due to the extraordinary growth in power consumption during the late 1960's and 1970's, many transformers were simply replaced with larger units. But today the continued operation of aging transformers is crucial to the financial performance and economic viability of the electric utility. The

[83] The Hartford Steam Boiler Inspection and Insurance Company, Life Cycle Management of Utility Transformer Assets, paper presented at Breakthrough Asset Management for the Restructured Power Industry October 10–11, 2002 Salt Lake City, Utah

transformer engineer and/or the asset manager are regularly expected to make timely replacement decisions on aging transformers. Transformer replacement is no longer a unilateral or arbitrary decision process. Substantial technical and financial data specific to the individual transformer, plus demographics, load growth, and overall performance of the transformer population must be taken into consideration. The decision to defer a replacement should no longer be a simple Net Present Value analysis. The decision should also include an increased risk calculation. The probability of failure for an "old" transformer is not constant; it is increasing exponentially each year. Obviously, this requires an in-depth knowledge of the corporate risk tolerance, current investment strategy (and "hurdle rates"), and the prevailing business and regulatory environment.

Approximately 99% (or even 100%) are recycled (source: T&D Europe (2009), the other are repaired or sold second hand.

CHAPTER 4 ASSESSMENT OF BASE-CASE

Scope:
This chapter comprises of an assessment of average EU product(s), the so called "base-cases" which is defined by the MEEuP as "a conscious abstraction of reality". Most of the environmental and life cycle cost analyses are built on these base-cases throughout the rest of the study, and serve as the point-of-reference for Task 5 (technical analysis BAT and BNAT), Task 6 (improvement potential), and Task 7 (policy and impact analysis).
The environmental impacts of the base-cases are assessed with the EuP EcoReport tool as specified in the MEEuP methodology and the specific inputs required for such an analysis (Bill of Materials, energy consumption during the use phase, etc) are presented. In particular, the contribution of the different phases of the life cycle to the environmental impacts is highlighted.

Summary:
Based on the European market analysis, seven base-cases are defined:

- Distribution transformers (400 kVA)
- Industry transformers: oil-immersed (1 MVA)
- Industry transformers: dry-type (1.25 MVA)
- Power transformers (100 MVA)
- DER transformers: oil-immersed (2 MVA)
- DER transformers: dry-type (2 MVA)
- Smaller industrial separation/isolation transformers (16 kVA)

The environmental impact assessment carried out with the EcoReport tool for each base-case shows that the use phase is by far the most impacting stage of the life cycle in terms of energy consumption, water consumption, greenhouse gases emissions and acidification (summary in Table 4-1 below). The production phase has a significant contribution to the following impacts: generation of non-hazardous waste, Volatile Organic Compounds, Persistent Organic Pollutants, Polycyclic Aromatic Hydrocarbons emissions and eutrophication. Finally, the end-of-life phase is significant for the generation of hazardous waste, the particulate matter emissions and the eutrophication, either due to mineral oil or resin. In particular, the impacts of mineral oil, whose impacts were added in the EcoReport tool, are visible but are also expected to be overestimated in this analysis. Indeed, the end-of-life modelling used the same environmental data as for plastics incineration (environmental impacts and credits) while burning mineral oil with energy recovery is expected to be more efficient than burning plastics with energy recovery. Therefore, the analysis of the improvement potential in chapter 6 focuses on technologies that reduce the electricity losses during the use phase, and also on alternative material (especially oil) reducing environmental impacts.
Despite a small amount of power transformers in stock, these transformers are responsible for about half of the overall impacts of the whole market of power and distribution transformers in EU. DER transformers still represent a very small share of the overall environmental impacts but it is expected to grow in the near future because of the rising stock of this type of transformer.

Environmental Impact	***BC1 Distribution***	***BC2 Industry oil***	***BC3 Industry dry***	***BC4 Power***	***BC5 DER oil***	***BC6 DER dry***	***BC7 Separation /isolation***
Total Energy (GER) *[PJ]*	201.35	152.91	47.72	379.24	2.71	11.66	4.73
of which electricity *[TWh]*	17.95	13.80	4.36	33.77	0.24	1.01	0.38
Waste, hazardous/ incinerated *[kton]*	41.90	24.67	2.38	89.94	0.53	0.65	0.09
Emissions to air							
Greenhouse Gases in GWP100 *[Mt CO_2 eq.]*	8.83	6.70	2.10	16.61	0.12	0.52	0.21
Volatile Organic Compounds (VOC) *[kt]*	0.14	0.09	0.02	0.28	0.00	0.01	0.00
Heavy Metals *[ton Ni eq.]*	5.79	4.07	0.95	11.50	0.08	0.25	0.26
Particulate Matter (PM, dust) *[kt]*	6.09	3.55	0.63	11.88	0.07	0.24	0.39
Emissions to water							
Eutrophication *[kt PO_4]*	0.05	0.03	0.01	0.08	0.00	0.00	0.00

Table 4-1: Environmental Impact per Base Case type of transformer

In general, the share of electricity in the Life Cycle Cost Analysis is significant (Table 4-2): from 53% for power transformers up to 88% for DER oil-immersed transformers. Only separation and isolation transformers have a bigger share related for the product price (77%) because of their lower availability factor and their shorter lifetime. Of the total consumer expenditure in 2005, electricity represents 59% of the global amount of money, estimated at 5 798 million Euros. Half of this annual expenditure is due to power transformers, which are much more expensive than the other types of transformers.

	BC1 Distribution	**BC2 Industry oil**	**BC3 Industry dry**	**BC4 Power**	**BC5 DER oil**	**BC6 DER dry**	**BC7 Separation /isolation**	**TOTAL**
EU-27 sales *[units]*	140 400	43 200	8 047	3 046	580	2 320	75 000	272 593
Share of the EU-27 sales	51.5%	15.8%	3.0%	1.1%	0.2%	0.9%	27.5%	100%
Product Price *[mln €]*	860	472	131	2 302	11	65	101	3 942
Electricity *[mln €]*	1 385	1 068	338	2 606	71	300	30	5 798
Total *[mln €]*	2 244	1 540	470	4 909	81	365	131	9 740

Table 4-2: Summary of Life Cycle Cost Analysis

4.1 Product specific inputs

This section describes the technical analysis of typical distribution and power transformers which exist on the EU market. This data will cover the production phase, the distribution phase, the use phase and the end-of-life phase. Bill of materials (BOM) and resource consumption during product life are some of the important parameters to be looked at[84,85]. This will be used as the general input for the definition of the base-cases, in section 4.2.

4.1.1 Methodology

Product data related to typical European transformer types and ratings has been collected thanks to an enquiry for stakeholders[86], discussions during the second stakeholder meeting and literature review. The typical power and distribution transformers within the scope of this study were defined in chapter 1 and are summarized in Table 4-3. In the inquiry, for each type and typical rating specified, stakeholders (manufacturers and operators) were asked to provide technical and economic data for two products: the first one being an average representative of the transformer type, and the other one(s) being an example of Best Available Technology (BAT) (e.g. very high efficiency).

As the environmental impact assessment requires information on the whole life cycle of products, the inquiry consisted of two forms: one questionnaire for the transformer manufacturers and one questionnaire for the operators. The questionnaire for the manufacturers was complemented with a spreadsheet designed to organize the Bill of Materials of transformers. Thus, manufacturers were able to provide data on the production and distribution phase and operators were more helpful about the end-of-life options and the use phase (e.g. load patterns). As previously specified, this enquiry was carried out to gather data about both average efficiency transformers and BAT transformers.

The main data asked for in the inquiry include:

- The rated power S [kVA];
- No load losses Po [W], and load losses Pk [W] at 75 °C;
- Reference price [Euro];
- The Bill of Materials, the use of consumables (oil, water…);
- Other performance parameters: Primary and secondary voltage, dimensions, sound pressure level, classes…

[84] Necessary input into EuP EcoReport.
[85] Environmental Product Declaration of ABB Distribution transformer 315kVA, 11kV, 3 phase, ONAN. Available at: http://library.abb.com/global/scot/scot292.nsf/veritydisplay/4dab3195c6221de4c1256d630041447f/$File/EPDdtr2.pdf
[86] Available at: www.ecotransformer.org

Type	Average rating S [kVA]	Typical no-load loss Po [W]	Typical load loss Pk [W] at 75°C
MV/LV Distribution oil-immersed	400	750 (D0)	4 600 (Ck)
Industry oil-immersed	1 000	1 700 (E0)	10 500 (Ck)
Industry dry-type	1 250	2 800	13 100
Power (primary voltage 132 kV, secondary voltage 33 kV)	100 000	40 500	326 000
DER oil-immersed	2 000	3 100 (E0)	21 000 (Ck)
DER dry-type	2 000	4 000	18 000
Separation/isolation	16	110	750

Table 4-3: Overview of the typical transformers in the inquiry

For the assessment of the base-cases and improvement options in later sections a hybrid approach was used based on aggregated product data from the stakeholder inquiry combined with technical data found in the literature. A simplified engineering analysis based on scaling relationships in transformer manufacturing (e.g. DOE, 2007)[87] was also used to extrapolate data and fit the base-cases performance to the market data included in chapter 2. Chapter 5 includes a more detailed description of this approach.

These relationships enable to scale some parameters (cost, dimension, losses…) to an equivalent transformer having a given rated power (see Table 4-4). Thus, even if the data is not referring to a transformer with the same rated power as the base-case, the scale values could be used and included into the engineering analysis. This approach was nonetheless only used for transformers with similar efficiency to the base-cases, so that the scaling relationships are still valid.

[87] DOE (2007): 'Technical support document: Energy efficiency program for commercial and industrial equipment: electrical distribution transformers', September 2007, U.S. Department of Energy.

Parameter Being Scaled	*Relationship to kVA Rating (varies with ratio of kVA^x)*
Weight	$(kVA_1/kVA_0)^{3/4}$
Cost	$(kVA_1/kVA_0)^{3/4}$
Length	$(kVA_1/kVA_0)^{1/4}$
Width	$(kVA_1/kVA_0)^{1/4}$
Height	$(kVA_1/kVA_0)^{1/4}$
Total Losses	$(kVA_1/kVA_0)^{3/4}$
No-load Losses	$(kVA_1/kVA_0)^{3/4}$

Table 4-4: Common scaling relationships in transformers (DOE, 2007[88])

4.1.2 Production phase modelling

Production phase data related to typical European transformers are derived from the BOM, product cost and sound pressure level. These are important input parameters in the calculation of the environmental impacts and product life cycle cost. The BOM has been collected from literature and the stakeholder inquiry. It is structured according to the different subassemblies or components in order to keep track of the material use per basic functionality (e.g. core with magnetic coupling).

The main subassemblies or components in transformers are presented in Table 4-5 (see also definitions in chapter 1):

Main components	*Subcomponents*	*Materials*
Coil/Windings	• Conductor • Insulation material • Coil Support Material	Copper, Aluminium, paper, cardboard, resin, porcelain
Magnetic core	• Magnetic Steel (Cold rolled grain oriented steel, amorphous steel…)	Magnetic Steel
Tank/Frame		Mechanical Steel, Aluminium
Cooling/Insulation liquid or gas		Mineral or biodegradable oil, air
Cast Compound	• Bushings	
Coatings		Powder coating, Paint
Auxiliary equipment	• Fans • Pumps • Monitoring/protection/control devices	
Electric assembly	• Electric panel • Cables	

Table 4-5: Main composition of a typical transformer

The materials forming the active part (copper or aluminium for the windings and magnetic steel for the magnetic core) dominate the material content from an optimal design and cost point of view.

88 DOE (2007): 'Technical support document: Energy efficiency program for commercial and industrial equipment: electrical distribution transformers', September 2007, U.S. Department of Energy.

4.1.2.1 Brief material composition of a transformer

This section briefly presents the typical components of a transformer[89].

- ***Coil/windings and insulation materials***

The windings are made as concentric shells around the core or for shell type transformers the core is around the coil. Primary windings are getting the voltage applied to the transformer and induce a magnetising current. Secondary windings are converting back the magnetic flux to an electric current in the secondary circuit.

Copper (Cu) and Aluminium (Al) are the two options for conductor materials in the windings for technical and economical reasons (primary and secondary windings are not necessarily made out of the same material). As the global copper and aluminium markets are fluctuating, the changes of availability and prices of these two materials can influence the choice of one material over the other. Copper windings are usually considered more efficient and result in smaller transformers than aluminium windings.

The windings have to be insulated (normally coated by varnish or paper) in order to force the current to go through every turn of the coil and reduce the losses. The benefits of varnish over paper are that the winding space factor is reduced due to smaller thickness and so is the "winding to liquid" temperature gradient.

The required properties to have a good insulation material are a high dielectric strength, good mechanical properties, a long lifetime at operating temperature and be easily workable. In liquid-immersed types, the material must of course be compatible to the liquid. The dominant insulation materials used for transformers with thermal class 105 are cellulose products such as high density paper and pressboard, which have a long lifetime and a high dielectric strength. They are also compatible to mineral oil and easy to oil impregnate. Other insulation materials used as support include wood (for liquid-immersed) and porcelain (for dry-type). Synthetic materials are usually used in dry-type transformers or in transformers having higher thermal classes (130, 155, 180, 220). They are more expensive than cellulose materials: enamels, epoxy resins, polyesters and aramid fibre (used to manufacture insulation paper or board sheets) are some of examples of these.

- ***Magnetic core***

The magnetic core is formed as a closed loop for the magnetic field and increases significantly the magnetic flux between the windings. The core design and core steel properties are the parameters having an influence on the no-load losses.

Transformer cores are built from thin sheets of specifically manufactured steel. They have a low carbon content (<30 ppm to reduce losses) and are commonly alloyed with silicon (content <3.5%), which enables the reduction of the eddy current losses in the core. The steel sheets have to be thin as the eddy current losses are proportional to the square of the thickness. Typical thickness is from 0.18 mm to 0.35 mm.

Grain-oriented Electrical Steel (GO) steel is steel whose magnetic domains tend to be oriented in the rolling direction. It is very widely used as core material because of its very good loss properties (only in the rolling direction) and is available in several grades depending on its composition and possible finishing treatments (e.g. laser

[89] Main source: ABB Transformer Handbook (2007), 3rd edition.

treatment). Like the windings, the core is insulated with an inorganic material which reduces the eddy current losses.
Amorphous steel, which has very low no-load losses properties, will be presented in detail in chapter 5 as it is considered as a Best Available Technology (BAT).

- ***Tank/frame***

The tank has four purposes: it contains the oil in liquid-immersed transformers, protects the active part from the exterior environment, allows the transmission of heat between the active part and the cooling devices and is a support structure for the accessories and control equipment.

The design of the tank can be challenging in some cases: for large transformers, the tank dimensions have to be kept within the specified transport profile, but the active part also needs to be enclosed in the tank with necessary insulation clearances. The resonance frequencies of the tank may also enhance the sound levels if they match the sound frequencies generated by the core.

- ***Cooling/insulation liquid or gas***

The fluid in a transformer mainly aims at cooling and insulating but also carries information about the condition of the active part. Requirements for an efficient fluid include:

- Chemical properties: oxidation stability and inhibitor content, water content, neutralization value;
- Physical properties: viscosity, density, surface tension, pour point;
- Electrical properties: breakdown voltage, dissipation factor, streaming charging;
- Others: low particle content, aromatic and poly-aromatic structure, solubility properties, etc.

Mineral oil is the dominant insulating liquid and is used as a reference to compare other liquids. It represents the best compromise between cost and technical properties, and offers a very good compatibility with other materials used in transformers. To maintain good dielectric properties, the oil needs to be clean and with low moisture content.

PCB used to be included in transformer oil. Because it is harmful to the environment and develops cancer-causing dioxides during normal combustion, its use is now prohibited and only PCB-free oils are being used. However, while most of the 12 chemicals covered by the Stockholm Convention are subject to an immediate ban, existing equipment containing PCBs may be maintained in a way that prevents leaks until 2025.
Today, gas (SF6) is rarely used as an insulation fluid in power transformers and thus will not be discussed in this study.

- ***Cast compound***

Porcelain or epoxy cast for distribution transformers is mainly used for bushings in oil-immersed transformers.

- ***Coatings***

Surface treatment depends on the transformer type and its ambient conditions, e.g. the weather conditions to which the transformer will be exposed. For instance, the worst conditions usually occur next to salt water and such situation may require a greater coat thickness. Large transformers are usually wet painted with a two-component epoxy base primer and a final coat, while small ones can be wet painted, powder coated or hot dip galvanized. The pre-treatment is of paramount importance for a good and lasting coating, blast cleaning being the most used technique.

The inside of large transformers is generally painted with epoxy paint inert to the oil and with good dielectric properties. The colour is usually light as it shows more easily possible contamination on the inside of the tank.

4.1.2.2 EcoReport BOM

Other specific production inputs that were asked for in the stakeholder enquiry include the quantity of silver (Ag) used for soldering and the sheet metal scrap percentage due to manufacturing processes. Because of lack of data, the silver weight will not be included in this analysis but this material should have a negligible influence on the final results, given the limited amount used.

Because the EcoReport was initially designed as a simple and generic tool for Ecodesign preparatory studies, its database does not include some materials found in transformers, such as:

- Different types of magnetic steel: cold rolled grain oriented, amorphous, etc.
- Oil (mineral or biodegradable);
- Wood;
- Ceramic/Porcelain.

Given the specificity of the magnetic steel, little data is available on the production impacts of the different range of steel. The embodied energy of two material categories was nonetheless amended in the EcoReport database in order to be more representative of the specific properties of the electric steel. Thus, the energy required to manufacture 1 kg of "steel sheet galvanised" was assessed at 73.4 MJ (to be used for the core steel) and the energy required to manufacture 1 kg of "steel tube/profile" at 28.8 MJ[90] (to be used for the tank steel). However, all types of core steel were input as "Material 21: Steel sheet galvanised" according to the material categories included in the EcoReport database. This is an important assumption which induces that **the differences of environmental impacts between the different types of steel are expected to be negligible in comparison with the global environmental impacts over the whole lifecycle.** This will be confirmed by the environmental impact assessment (section 4.3).

The three other materials (mineral oil, wood and ceramics) were added to the database. Their environmental impacts (oil and wood extracted from the EcoInvent 2.0 database, ceramics from ETH-ESU 96) are presented in Table 4-6 and Table 4-7 below.
It was not possible to obtain all the environmental impacts for the three materials. However, the categories cooling water, hazardous waste and non-hazardous waste are not supposed to be of paramount importance in the environmental analysis. The category feedstock energy is only useful when the material is thermally recycled during the end-of-life management, which is only the case for mineral oil here.

[90] Thanks to CLASP co-operation, through GaBi 4 software.

For 1 kg	Gross Energy [MJ]	Electricity [MJ]	Feedstock Energy [MJ]	Process Water [L]	Cooling Water [L]	Hazardous Waste [g]	Non-Hazardous Waste [g]
Mineral Oil	53.75	0.28	52.02	5.47	6.89	-	35.32
Wood	23.84	2.82	-	3.57	-	-	133.78
Ceramics	6.89	0.40	-	-	-	-	-

Table 4-6: Calculated impacts per kg of material[91]

For 1 kg	Air							Water
	Global Warming Potential [kg CO2 eqv]	Acidification Potential [g SO2 eq]	Volatile Organic Compounds [g]	Persistant Organic Pollutants [ng I-Teq]	Heavy Metals [mg Ni eq]	Polycyclic Aromatic Hydrocarbons [mg Ni eq.]	Particulate Matter [g]	Eutrophication Potential [g PO4]
Mineral Oil	0.46	5.75	1.16	0.12	1.16	15.00	0.33	0.56
Wood	0.39	2.23	1.47	0.03	0.80	50.06	0.55	0.33
Ceramics	0.37	1.46	0.14	0.00	0.16	1.05	0.26	0.14

Table 4-7: Calculated emissions per kg of material[92]

No category entitled 'mineral oil' was available in Life Cycle Inventories. Thus, the modelling of mineral oil was achieved according to the typical composition of such oil and with available materials in the database: 70% by weight of light fuel oil and 30% by weight of heavy fuel oil. The specific processes of the mineral oil refinery are not known and were not environmentally assessed. Therefore these impacts are expected to be most accurate possible.

The conversion factor 1 kWh_e = 10.5 MJ given in the MEEuP was used to convert the electricity consumption. When impacts were assessed from the inventory, the weighting factors defining the level of contribution of different chemical compounds to air and water emissions were extracted from the MEEuP in order to calculate the emission impacts per kg of material. For instance, about the Global Warming Potential (GWP) impact, carbon dioxide equivalence is defined to express the final results in kg CO_2: carbon dioxide accounts for 1, while methane has a weighting of 21 and sulphur hexafluoride of 22 200. It basically means that 1 kg of methane has an impact 21 times more important than 1 kg of carbon dioxide in terms of global warming.

In the EcoReport spreadsheet, mineral oil was added as a 'plastic material' in the subsection "1-BlkPlastics", replacing a plastic type not used during this study. The aim of such an addition was to apply the same end-of-life parameters as plastics to oil, in order to be able to choose the thermal recycling option (see 4.2.1), which reduces the environmental impacts of the end-of-life phase. An attempt was made to gather specific impacts of the oil incineration, instead of using the default values referring to plastics incineration. In the EcoInvent LCI, a category 'Disposal, used mineral oil, 10% water, to hazardous waste incineration' is present. However, the resulting environmental impacts calculated were very different from the ones already present in EcoReport (e.g. 67 MJ for Gross energy requirement in EcoReport vs. 0.49 MJ calculated from LCI). As a result, it was decided to keep the default values of EcoReport to deal with the end-of-

[91] Gross energy, process water and non-hazardous waste impacts calculated with method: CML 2 baseline 2000 v2.04 and IMPACT 2002+_CIRAIG 09-07-2008. Other impacts assessed only from inventory.
[92] GWP, Acidification potential and Eutrophication potential impacts calculated with method CML 2 baseline 2000 v2.04 and compliance with direct calculations from inventory checked. Other impacts assessed only from inventory.

life of the oil. The environmental impacts due to oil may thus be overestimated as burning fuel with energy recovery is in theory more efficient than burning plastics with energy recovery. This will be kept in mind for the environmental analysis.
'Wood' and 'Ceramics' were added as 'Miscellaneous' materials in the subsection '7-Misc.' of the EcoReport, replacing 'Bitumen' and 'Concrete'.

4.1.3 Distribution phase modelling

Input data related to the distribution phase of the product to be used in the MEEuP EcoReport calculations are based on the volume of the packaged product, which is calculated from the dimensions extracted from the BOM.

4.1.4 Use phase modelling

4.1.4.1 Energy consumption

The energy consumption during the use phase is expected to be the main contributor to the environmental impacts of a transformer. The annual energy consumption is required as an input in EcoReport, as well as the product lifetime which was evaluated in the market analysis (see chapter 2). These inputs will also be used to calculate the Life Cycle Costs (LCC) of the base-cases.

The main input data related to the use phase of a transformer is the electricity consumption (losses) of the transformer under specific load conditions. This energy consumption is calculated using the usage parameters shown in Table 4-8 and the product specific no-load loss Po (W) and load loss Pk (W). The related formulas were described in previous chapters 1 and 3. No-load loss Po and load loss Pk are the product related parameters and will be determined in section 4.2 for each base-case, based on the inquiry results and market analysis.

As the annual electricity losses is a paramount input for the environmental impact assessments and because several different methods exist to calculate the electricity losses, a sensitivity analysis on calculation parameters will be carried out in Chapter 6.

Typical transformer	***Load factors (α)***	***Load form factors (Kf)***	***Power factor (Pf)***	***Availability factor (Af)***	***Average Lifetime***
MV/LV distribution oil	0.15	1.073	0.9	1	40
Industry oil	0.30	1.096		1	25
Industry dry	0.30	1.096		1	30
Power	0.20	1.08		1	30

Typical transformer	***Load factors (α)***	***Load form factors (Kf)***	***Power factor (Pf)***	***Availability factor (Af)***	***Average Lifetime***
DER (liquid-immersed and dry-type)	0.25	1.50		1	25
Separation/isolation	0.40	1.096		0.2	10

Table 4-8: Usage parameters as defined in chapter 3

The annual electricity losses were calculated according to Formula 3.2 (already presented in Chapter 3):

$$Etr(y)\ [kWh] = Af \times (P_o[W] + P_k[W] \times (\alpha \times K_f/PF)^2 + P_{aux}) \times 8\ 760/1\ 000$$

Where (see Chapter 1 for definitions of the following terms):

$Etr(y)$ = the energy used by the distribution transformer per year [kWh],
Af = availability factor,
P_o = no-load losses at rated load,
P_k = load losses at rated load,
P_{aux} = auxiliary losses,
α = load factor,
K_f = load form factor,
PF = the power factor of the load served by the transformer.

The load and no-load loss levels that were used in inputs for the calculations are the ones already presented in Table 4-3. The auxiliary losses were assumed to be negligible in this study due to lack of data.

Table 4-9 exposes the results of the annual losses calculations. These results strongly depend on the loading parameters used, presented in Table 4-8. Therefore, given the expected influence of the electricity losses in the environmental impacts and economic analysis, a sensitivity analysis will be carried out in Chapter 6.

	Inputs[93]		Outputs
Typical transformer	**Load losses [W]**	**No-load losses at 75°C [W]**	**Annual losses (according to Formula 3.2) [kWh]**
MV/LV distribution oil	750	4 600	7 859
Industry oil	1 700	10 500	27 168
Industry dry	2 800	13 100	39 844
Power	40 500	326 000	519 272
DER oil-immersed	3 100	21 000	59 093
DER dry-type	4 000	18 000	62 415
Separation/isolation	110	750	505

Table 4-9: Annual electricity losses of the seven base-cases

4.1.4.2 Product or investment cost

As explained in chapter 2, transformer prices are related to commodity prices, functionality and typical market circumstances such as demand and competition. Therefore, transformer prices fluctuate accordingly over time. It is not the purpose to start a bidding platform for transformers prices that could influence the current and future transformer market, but rather to allow a fair comparison of the relative impact related to improvement options. Therefore, it is proposed to apply an agreed reference price per transformer base-case.

A first attempt had been made to estimate the prices from the transformers design (mainly core and coil composition) but this approach did not appear relevant as many stakeholders complained about overestimated prices during the second stakeholder meeting. The simplified cost estimation was based on the fact that the cost of the active part represents around 35% of the purchase price of a transformer[94] (20% for power transformer). The prices of the active parts materials shown in Table 4-10 (already presented in Chapter 2) were used.

[93] The inputs concerning the loading profiles are presented in Table 4-8.
[94] Materials cost represents 60 % of the purchase price and core & windings represent 59% of the material cost. Source: Distribution Transformer Standards Rulemaking; U.S. Department of Energy August 2002.

<table>
<tr><th>Reference Type</th><th>Reference Po [W]</th><th>Reference Pk at 75°C [W]</th><th>Core Steel [€/Kg]</th><th>Windings Copper [€/Kg]</th><th>Windings Aluminium [€/Kg]</th><th>Mineral Oil [€/Kg]</th></tr>
<tr><td>MV/LV distribution oil</td><td>750 (D0)</td><td>4 600 (Ck)</td><td>3.0 (M140-30S)</td><td>4.54 (tube)
4.42 (wire)</td><td>2.58</td><td rowspan="2">1.0</td></tr>
<tr><td>Industry oil</td><td>1 700 (E0)</td><td>10 500 (Ck)</td><td>3.0 (M140-30S)</td><td>4.42 (wire)</td><td>2.58</td></tr>
<tr><td>Industry dry</td><td>2 800</td><td>13 100</td><td>1.60 (M150-35S)</td><td>4.85</td><td>3.48</td><td>-</td></tr>
<tr><td>Power</td><td>80 000</td><td>300 000</td><td>1.55 (M150-35S)</td><td>4.54 (tube)
4.42 (wire)</td><td>-</td><td rowspan="2">1.0</td></tr>
<tr><td>DER (oil-immersed)</td><td>3 100</td><td>21 000</td><td>3.0 (M140-30S)</td><td>4.54 (tube)
4.42 (wire)</td><td>2.58</td></tr>
<tr><td>DER (dry-type)</td><td>4 000</td><td>18 000</td><td>1.64 (M140-30S)</td><td>-</td><td>3.48</td><td>-</td></tr>
<tr><td>Separation /isolation</td><td>110</td><td>750</td><td>1.60 (M150-35S)</td><td>4.85</td><td>-</td><td>-</td></tr>
</table>

Table 4-10: Overview of reference transformer prices used in this study (not marked up, without taxes)

Consequently, another approach entirely relying on manufacturers inputs was used. Base-case prices were aggregated from the results of the inquiry launched after the second stakeholder meeting (see Annex B). The purchase prices will be presented later in Table 4-26.

In order to take the fluctuating transformer prices into account, a sensitivity analysis will be performed in Chapter 6 based on a price span (+/- %).

4.1.4.3 Sound level

It is assumed in this study that sound nuisance is reduced by using isolation materials or other sound reducing measures to achieve acceptable sound levels.

Sound levels are taken into account in the current EN standards for oil-filled distribution transformers. In the EN 50464-1 a specific sound level is given for every rated power and energy efficiency class. Sound levels range from 55 to 81 dB(A) for Eo transformers and from 42 to 66 dB(A) for Bo oil-filled transformers. According to this standard, it is obvious that the most efficient transformers also have lower sound levels; hence there is a synergy with the efficiency optimisation. Nevertheless, it will be further analysed in chapter 5 whether this is also the case for amorphous steel transformers (AMT). For dry-type transformers, the HD538 standard does not mention a related sound level.

4.1.5 End-of-life phase modelling

It is assumed that 99% of the transformer materials are recycled and reused (see Chapter 3). However, depending on the BOM of each base-case, this recycling ratio will be adapted according to the individual material recycling rate:

- metals are 100% recycled;
- paper, cardboard, plastics and oil are 100% incinerated or thermally recycled;
- other waste (ceramics) goes to landfill. Hazardous waste consists only of electronic components (very small quantity).

4.2 Definition of base-case

The objective of this section is to define and describe the base-cases, based on the previous tasks and the information recovered from the stakeholders and the literature review. The base-cases are “a conscious abstraction of reality” and have to cover the wide variety of existing power and distribution transformers in order to be representative of the European market as possible. Therefore, the number of base-cases is optimized to be small enough to enable a simplified analysis of the market but large enough to deal with the technological spectrum of transformers.

According to the MEEuP methodology, one or two base-cases should be defined to cover the scope of the preparatory study. However, because of the wide range of existing power and distribution transformers that have significant sales amounts, the study will deal with the seven following base-cases which are based on the typical transformers presented in the stakeholder enquiry:

- **BC 1 - Distribution transformer (400 kVA, P_0 750 W, P_k 4 600 W)**
- **BC 2 - Industry transformer: oil-immersed (1 MVA, P_0 1 700 W, P_k 10500 W)**
- **BC 3 - Industry transformer: dry-type (1.25 MVA, P_0 2 800 W, P_k 13 100 W)**
- **BC 4 - Power transformer (100 MVA, P_0 40 500 W, P_k 326 000 W, primary voltage 132 kV, secondary voltage 33 kV)**
- **BC 5 - DER transformer : oil-immersed (2 MVA, P_0 3 100 W, P_k 21 000 W)**
- **BC 6 – DER transformer : dry-type (2 MVA, P_0 4 000 W, P_k 18 000 W)**
- **BC 7 – Separation/isolation transformer (16 kVA, P_0 110 W, P_k 750 W)**

The following subsections present the EcoReport inputs related to each base-case.

4.2.1 General inputs and assumptions

Some inputs in the EcoReport were the same for all seven base-cases. These are presented in Table 4-11.

EcoReport Section	***EcoReport Input***	***Value***
Production phase	Sheetmetal Scrap	5%
Distribution phase	Is it an ICT or Consumer Electronics product <15 kg?	NO
	Is it an installed appliance (e.g. boiler)?	YES
Use phase	Heat-related	Not applicable for transformers
	Consumables (excl, spare parts)	None
	No. of km over Product-Life	500 km
Disposal and recycling	Substances released during product life and landfill (refrigerant, mercury...)	None
	Re-use, Recycling Benefit (only for plastics material and oil)	0% re-use and closed loop recycling, 0% materials recycling, 100% thermal recycling
	Electronics: PWB Easy to Disassemble?	YES
Inputs for EU-Totals & economic Life Cycle Costs	Fuel rate	Not applicable for transformers
	Electricity rate	0.078 Euro/kWh (for BC 1 to 4, & 7) 0.3 Euro/kWh (for BC 5 & 6)
	Consumables	Not applicable for transformers
	Discount rate	4%
	Overall improvement ratio	1 (except for BC 1 & 2)

Table 4-11: General EcoReport inputs for the seven base-cases.

- The sheetmetal scrap: according to GaBi[95], the modelling of the manufacture of a transformer results in 5% of internal scrap for steel parts and 3% scrap production for aluminium. As steel represents the major part of a transformer in terms of weight with both magnetic and mechanical steel (around 60%), the sheetmetal scrap percentage input in EcoReport was assumed to be 5% for all base-cases.

- The fraction landfilled had been previously estimated to be 1%, as 99% of transformers is recycled/re-used (see chapter 3). However, specific disposal rates will be provided in the specific inputs section.

- Consumables: the mineral oil of the transformer is normally not changed during the whole lifetime, except in case of specific issues (e.g. leakage) which is not taken into account in this study. The quantity of oil will be included in the BOM.

[95] More information available at: www.gabi-software.com

- An average distance of 500 km[96] over the product life was assumed.

- The re-use and recycling benefits of plastics values were changed for all base-cases: 0% re-use and closed loop recycling, 0% materials recycling and 100% thermal recycling were assumed. Indeed, mineral oil is considered as a plastic material in the specific EcoReport for this study so that these end-of-life options also apply to it. Given the comparison between plastics and oil weights in a typical transformer, it was relevant to apply a 100% rate for thermal recycling, which is what actually happens for oil (but not necessarily for plastics).

- The electricity rate was estimated at 0.078 Euro/kWh in Chapter 2 for all base-cases, except for DER transformers (BC 5 and 6) for which a rate of 0.3 Euro/KWh[97] has been applied.

- The discount rate has been estimated at 4% by the European Commission. If required, a sensitivity analysis on the parameter will be carried out in Chapter 6. This value will also be used for the TCO calculation in section 0.

- For distribution and industry-oil transformers, the overall improvement ratios (market over stock) were calculated from data in SEEDT while the other ratios were assumed to be 1.

4.2.2 Base-case 1 inputs: Distribution transformer

- Bill of Materials:

[96] PSR (2006): 'Liquid- or gas-filled and dry type transformers within the range of < 1000 MVA' (ref. PSR 2000:6), The Swedish Environmental Management Council Version 1.1 2001-02-21.
[97] Statistics available at: www.recs.org

Nr	Product name	Date	Author
1	**BC1 - Distribution transformer**		**BIO**

Pos nr	MATERIALS Extraction & Production Description of component	Weight in g	Category Click &select	Material or Process select Category first !
1	CORE			
2	Core steel	468700.0	3-Ferro	**21-St sheet galv.**
3				
4	WINDINGS			
5	Aluminum wire	21440.0	4-Non-ferro	**26-Al sheet/extrusion**
6	Copper wire	144720.0	4-Non-ferro	**28-Cu winding wire**
7	Copper sheet	48240.0	4-Non-ferro	**30-Cu tube/sheet**
8				
9	TANK			
10	Steel	266696.2	3-Ferro	**22-St tube/profile**
11				
13	INSULATION			
14	Paper	15996.6	7-Misc.	**57-Office paper**
16	Ceramic	6019.4	7-Misc.	**55-Ceramics**
17	Oil	265500.0	1-BlkPlastics	**4-Mineral Oil**
18	Cardboard	3654.0	7-Misc.	**56-Cardboard**
20				
21	OTHERS			
22	Plastics	2046.2	1-BlkPlastics	**2-HDPE**
23	Wood	4384.8	7-Misc.	**58-Wood**
24				
25	COATINGS	5786.3	5-Coating	**39-powder coating**

Table 4-12: EcoReport material input table for BC 1

- Volume and weight of the packaged final product: 2.11 m^3 / 1 253 kg
- Product life: 40 years
- Energy use during use phase: 7.9 MWh per year
- Fraction not recovered (landfill): 1%
  This fraction is the percentage of ceramics (the only material being landfilled) in the global weight of the transformer.
- Overall improvement ratio: 1.0039

4.2.3 Base-case 2 inputs: Industry oil transformer

- Bill of Materials:

Nr	Product name	Date	Author
2	BC2 - Industry oil-immersed		BIO

Pos nr	MATERIALS Extraction & Production Description of component	Weight in g	Category Click &select	Material or Process select Category first !
1	CORE			
2	Core steel	882200.0	3-Ferro	21-St sheet galv.
3				
4	WINDINGS			
5	Aluminum wire	64320.0	4-Non-ferro	26-Al sheet/extrusion
6	Copper wire	364480.0	4-Non-ferro	28-Cu winding wire
8				
9	TANK			
10	Steel	601689.3	3-Ferro	22-St tube/profile
11				
13	INSULATION			
14	Paper	25862.6	7-Misc.	57-Office paper
16	Ceramic	5284.7	7-Misc.	55-Ceramics
17	Oil	493900.0	1-BlkPlastics	4-Mineral Oil
18	Cardboard	8923.7	7-Misc.	56-Cardboard
20				
25	COATINGS	4457.0	5-Coating	39-powder coating

Table 4-13: EcoReport material input table for BC 2

- Volume of and weight of the packaged final product: 3.20 m^3 / 2 451 kg
- Product life: 25 years
- Energy use during use phase: 27.2 MWh per year
- Fraction not recovered (landfill): 1%
- Overall improvement ratio: 1.0001

4.2.4 Base-case 3 inputs: Industry dry transformer

- Bill of Materials:

Nr	Product name	Date	Author
3	BC3 - Industry dry		BIO

Pos nr	MATERIALS Extraction & Production Description of component	Weight in g	Category Click &select	Material or Process select Category first !
1	CORE			
2	Core steel	1872957.0	3-Ferro	21-St sheet galv.
3				
4	WINDINGS			
5	Aluminum wire	355448.0	4-Non-ferro	26-Al sheet/extrusion
6	Copper wire	104826.0	4-Non-ferro	28-Cu winding wire
8				
9	TANK			
10	Steel	118792.5	3-Ferro	22-St tube/profile
12				
13	INSULATION			
15	Resin	145958.2	2-TecPlastics	14-Epoxy
16	Ceramic	60777.5	7-Misc.	55-Ceramics
18				
19	COATINGS	1381.3	5-Coating	39-powder coating
20				
21	OTHERS			
22	Plastics	16115.3	1-BlkPlastics	2-HDPE

Table 4-14: EcoReport material input table for BC 3

- Volume of and weight of the packaged final product: 2.936 m^3 / 2 676 kg
- Product life (see chapter 2): 30 years
- Energy use during use phase: 39.8 MWh per year
- Fraction not recovered (landfill): 2.3%
  This fraction is the percentage of ceramics (the only material being landfilled) in the global weight of the transformer.
- Overall improvement ratio: 1

4.2.5 Base-case 4 inputs: Power transformer

- Bill of Materials:

Nr	Product name	Date	Author
4	BC 4 - Power transformer		BIO

Pos nr	MATERIALS Extraction & Production Description of component	Weight in g	Category Click &select	Material or Process select Category first !
1	CORE			
2	Core steel	39486668.0	3-Ferro	21-St sheet galv.
3				
4	WINDINGS			
6	Copper wire	17487837.8	4-Non-ferro	28-Cu winding wire
7	Copper sheet	1204750.2	4-Non-ferro	30-Cu tube/sheet
8				
9	TANK			
10	Steel	11306995.4	3-Ferro	22-St tube/profile
12				
13	INSULATION			
14	Paper	504535.3	7-Misc.	57-Office paper
16	Ceramic	472325.1	7-Misc.	55-Ceramics
17	Oil	26848483.2	1-BlkPlastics	4-Mineral Oil
18				
19	Coatings	391718.7	5-Coating	39-powder coating
20				
21	OTHERS			
23	Wood	2672738.0	7-Misc.	58-Wood

Table 4-15: EcoReport material input table for BC 4

- Volume of and weight of the packaged final product: 188.76 m^3 /100 376 kg
- Product life: 30 years
- Energy use during use phase: 519.3 MWh per year
- Fraction not recovered (landfill): 1%
- Overall improvement ratio: 1

4.2.6 Base-case 5 inputs: DER oil transformer

- Bill of Materials:

Nr	Product name	Date	Author
5	BC 5 - DER (oil-immersed)		BIO

Pos nr	MATERIALS Extraction & Production Description of component	Weight in g	Category Click &select	Material or Process select Category first !
1	CORE			
2	Core steel	1715467.0	3-Ferro	21-St sheet galv.
3				
4	WINDINGS			
5	Aluminum wire	190435.4	4-Non-ferro	26-Al sheet/extrusion
6	Copper wire	542740.9	4-Non-ferro	28-Cu winding wire
7	Copper sheet	219000.7	4-Non-ferro	30-Cu tube/sheet
8				
9	TANK			
10	Steel	1113008.9	3-Ferro	22-St tube/profile
11				
13	INSULATION			
14	Paper	10307.2	7-Misc.	57-Office paper
17	Oil	800304.2	1-BlkPlastics	4-Mineral Oil
18	Cardboard	10616.4	7-Misc.	56-Cardboard
19	Nomex	21687.1	2-TecPlastics	19-Aramid fibre
24				
25	COATINGS	4321.0	5-Coating	39-powder coating

Table 4-16: EcoReport material input table for BC 5

- Volume of and weight of the packaged final product: 4.02 m^3 / 4 628 kg
- Product life: 25 years
- Energy use during use phase: 59.1 MWh per year
- Fraction not recovered (landfill): 1%
- Overall improvement ratio: 1

4.2.7 Base-case 6 inputs: DER dry transformer

- Bill of Materials:

Nr	Product name	Date	Author
6	BC 6 - DER dry transformer		BIO

Pos nr	MATERIALS Extraction & Production Description of component	Weight in g	Category Click &select	Material or Process select Category first !
1	CORE			
2	Core steel	3568822.0	3-Ferro	21-St sheet galv.
3				
4	WINDINGS			
5	Aluminum wire	841004.1	4-Non-ferro	26-Al sheet/extrusion
8				
9	TANK			
10	Steel	415646.4	3-Ferro	22-St tube/profile
11				
13	INSULATION			
15	Resin	112513.7	2-TecPlastics	14-Epoxy
16	Ceramic	221425.0	7-Misc.	55-Ceramics
20				
21	OTHERS			
22	Plastics	59900.0	1-BlkPlastics	2-HDPE
24				
25	COATINGS	5556.0	5-Coating	39-powder coating

Table 4-17: EcoReport material input table for BC 6

- Volume of and weight of the packaged final product: 4.26 m^3 / 5 225 kg
- Product life: 25 years
- Energy use during use phase: 62.4 MWh per year
- Fraction not recovered (landfill): 4.2%
  This fraction is the percentage of ceramics (the only material being landfilled) in the global weight of the transformer.
- Overall improvement ratio: 1

4.2.8 Base-case 7 inputs: Separation/isolation transformer

- Bill of Materials:

Nr	Product name	Date	Author
7	BC 7 - Separation/isolation		BIO

Pos nr	MATERIALS Extraction & Production Description of component	Weight in g	Category Click &select	Material or Process select Category first !
1	CORE			
2	Core steel	50000.0	3-Ferro	21-St sheet galv.
3				
4	WINDINGS			
6	Copper w ire	35000.0	4-Non-ferro	28-Cu winding wire

Table 4-18: EcoReport material input table for BC 7

- Volume of and weight of the packaged final product: 0.04 m^3 / 85 kg
- Product life: 10 years
- Energy use during use phase: 505 kWh per year
- Fraction not recovered (landfill): 1%
- Overall improvement ratio: 1

4.3 Base-case Environmental Impact Assessment

The aim of this subtask is to assess the environmental impact of each base-case following the MEEuP (EcoReport Unit Indicators) for each life cycle stage:

- Raw Materials Use and Manufacturing (Production phase);
- Distribution phase;
- Use phase;
- End-of-Life.

The base-case environmental impact assessment will lead to an identification of basic technological design parameters being of outstanding environmental relevancy[98]. These parameters will be listed as they will serve as an important input to the identification of eco-design options.

The assessment results are tracked back to the main contributing components, materials and features of the power and distribution transformers.

[98] As far as the MEEuP EcoReport allows the identification of such indicators.

4.3.1 Base-case 1: Distribution transformer

Table 4-19 shows the environmental impacts of a distribution transformer over its whole life cycle. The total energy consumption for the whole life cycle of the distribution transformer base-case is 3.41 TJ, of which 3.32 TJ (i.e. 316 MWh[99]) electricity.

Nr	Life cycle Impact per product:	Date	Author
1	BC1 - Distribution transformer	0	BIO

Nr	Life Cycle phases --> / Resources Use and Emissions	unit	PRODUCTION Material	PRODUCTION Manuf.	PRODUCTION Total	DISTRI-BUTION	USE	END-OF-LIFE* Disposal	END-OF-LIFE* Recycl.	END-OF-LIFE* Total	TOTAL
	Materials	**unit**									
1	Bulk Plastics	g			**267546**			267546	0	**267546**	**0**
2	TecPlastics	g			**0**			0	0	**0**	**0**
3	Ferro	g			**735396**			7354	728042	**735396**	**0**
4	Non-ferro	g			**214400**			2144	212256	**214400**	**0**
5	Coating	g			**5786**			58	5728	**5786**	**0**
6	Electronics	g			**0**			0	0	**0**	**0**
7	Misc.	g			**30055**			301	29754	**30055**	**0**
	Total weight	g			**1253183**			277403	975781	**1253183**	**0**
									see note!		
	Other Resources & Waste							debet	credit		
8	Total Energy (GER)	MJ	79729	19397	**99127**	**2395**	**3302858**	18861	14653	**4208**	**3408587**
9	of which, electricity (in primary MJ)	MJ	2855	11615	**14470**	**6**	**3300807**	0	0	**0**	**3315283**
10	Water (process)	ltr	2829	173	**3001**	**0**	**220074**	0	0	**0**	**223076**
11	Water (cooling)	ltr	4115	5417	**9531**	**0**	**8801863**	0	0	**0**	**8811394**
12	Waste, non-haz./ landfill	g	4405405	64619	**4470024**	**1009**	**3871631**	15363	0	**15363**	**8358027**
13	Waste, hazardous/ incinerated	g	252	2	**254**	**20**	**76059**	267546	0	**267546**	**343879**
	Emissions (Air)										
14	Greenhouse Gases in GWP100	kg CO2 eq.	3356	1080	**4436**	**142**	**144176**	1406	1094	**313**	**149067**
15	Ozone Depletion, emissions	mg R-11 eq.					negligible				
16	Acidification, emissions	g SO2 eq.	54897	4660	**59557**	**434**	**850609**	2801	1370	**1431**	**912031**
17	Volatile Organic Compounds (VOC)	g	420	4	**424**	**44**	**1267**	41	19	**22**	**1756**
18	Persistent Organic Pollutants (POP)	ng i-Teq	16599	290	**16889**	**6**	**21803**	114	0	**114**	**38812**
19	Heavy Metals	mg Ni eq.	12526	679	**13205**	**51**	**57019**	5066	0	**5066**	**75342**
	PAHs	mg Ni eq.	7380	4	**7384**	**95**	**6836**	0	0	**0**	**14315**
20	Particulate Matter (PM, dust)	g	2617	718	**3334**	**7212**	**22597**	23782	23	**23759**	**56902**
	Emissions (Water)										
21	Heavy Metals	mg Hg/20	5589	0	**5589**	**2**	**21338**	1590	0	**1590**	**28519**
22	Eutrophication	g PO4	208	10	**217**	**0**	**104**	91	0	**91**	**412**
23	Persistent Organic Pollutants (POP)	ng i-Teq					negligible				

Table 4-19: Life Cycle Impact (per unit) of base-case 1 – Distribution

Figure 4-1 exposes the contribution of each life cycle phase to each impact. Several observations can be made from this analysis:

- Within the production phase, the impacts due to the manufacturing processes are very low (maximum of 2 % for eutrophication). However, the extraction and production of raw material significantly contributes to some emissions, such as volatile organic compounds (VOC) (24%), persistent organic pollutants (POP) (43%) eutrophication (50%) or polycyclic aromatic hydrocarbons (PAHs) (52%), as well as to the generation of non-hazardous waste because of the high steel and copper content (53%). Core steel is the main material responsible for POP emissions. Aluminium and oil induce high PAHs impacts.

[99] The MEEuP specifies a value of 10.5 MJ/kWh$_e$, for electricity from the public grid.

- The use phase accounts for 97% of the energy consumption over the whole life cycle, more than 99.5% of the electricity use and 96.7% of the greenhouse gases emissions. These impacts are almost exclusively due to the electricity losses during the use phase, with maintenance and spare parts impacts being negligible.
- The distribution phase is negligible for all impacts except for Particulate Matter (PM) for which it accounts for around 13% of the emissions because of the transformer transportation.
- Finally, the end-of-life accounts for 78% of the hazardous waste generated, 42% of PM emissions to the air, 22% of the eutrophication impacts and 7% of heavy metals emissions. For all other impacts, it has a negligible influence. The incineration of oil is the main reason for the high contributions to hazardous waste, PM and eutrophication, even if it also reduces slightly the energy consumption over the whole life cycle because of the energy recovery process.

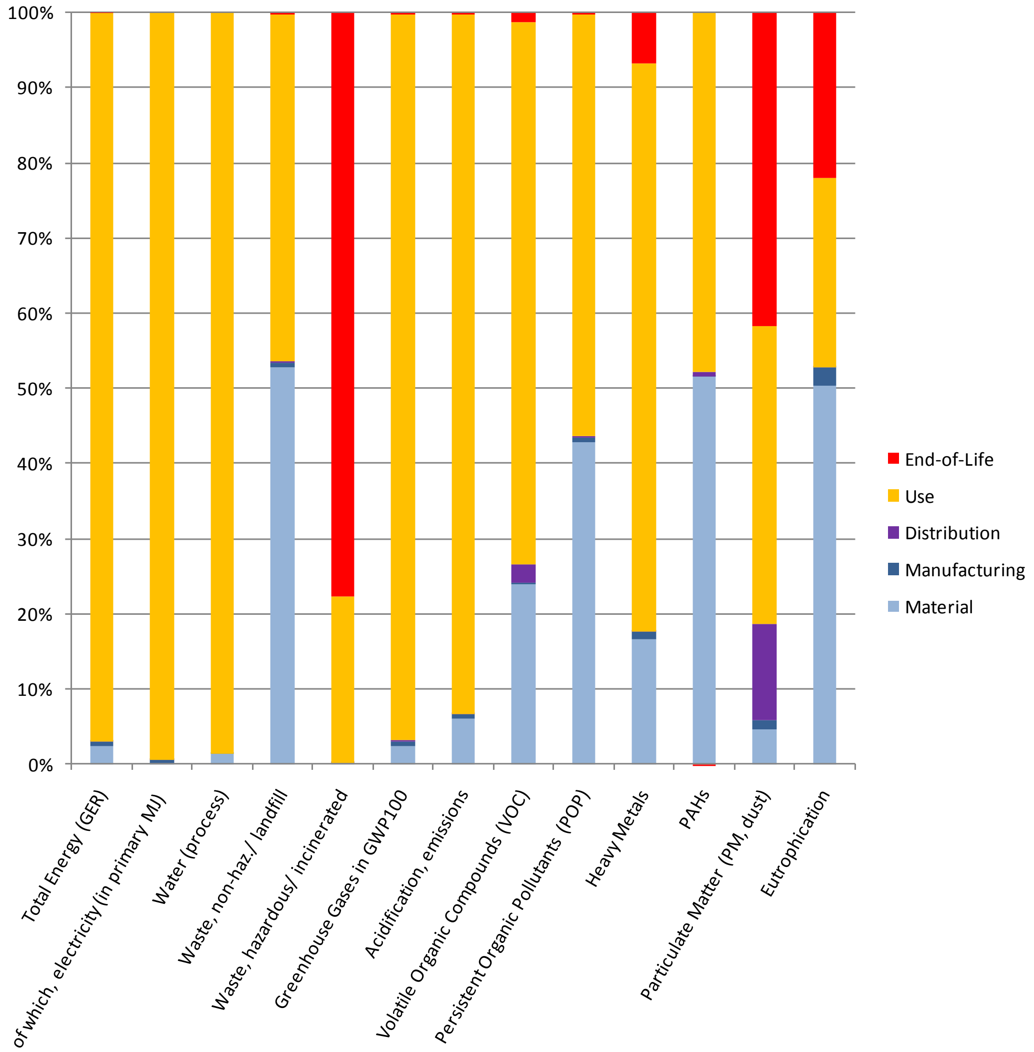


Figure 4-1: Distribution of environmental impacts of BC 1 per life cycle phase

4.3.2 Base-case 2: Industry oil transformer

Table 4-20 shows the environmental impacts of an industry oil-immersed transformer over its whole life cycle. The total energy consumption for the whole life cycle of this transformer base-case is 7.34 TJ, of which 7.16 TJ (i.e. 682 MWh) electricity.

Nr	Life cycle Impact per product:	Date	Author
2	BC2 - Industry oil-immersed		BIO

Nr	Life Cycle phases -->		PRODUCTION			DISTRI-	USE	END-OF-LIFE*			TOTAL
	Resources Use and Emissions		Material	Manuf.	Total	BUTION		Disposal	Recycl.	Total	
	Materials	unit									
1	Bulk Plastics	g			**493900**			493900	0	**493900**	**0**
2	TecPlastics	g			**0**			0	0	**0**	**0**
3	Ferro	g			**1483889**			14839	1469050	**1483889**	**0**
4	Non-ferro	g			**428800**			4288	424512	**428800**	**0**
5	Coating	g			**4457**			45	4412	**4457**	**0**
6	Electronics	g			**0**			0	0	**0**	**0**
7	Misc.	g			**40071**			401	39670	**40071**	**0**
	Total weight	g			**2451117**			513472	1937645	**2451117**	**0**
									see note!		
	Other Resources & Waste							debet	credit		
8	Total Energy (GER)	MJ	162838	35063	**197901**	**3602**	**7134895**	34912	26696	**8215**	**7344613**
9	of which, electricity (in primary MJ)	MJ	5348	21000	**26347**	**9**	**7131976**	0	0	**0**	**7158332**
10	Water (process)	ltr	4818	312	**5131**	**0**	**475499**	0	0	**0**	**480630**
11	Water (cooling)	ltr	5114	9796	**14910**	**0**	**19018048**	0	0	**0**	**19032959**
12	Waste, non-haz./ landfill	g	9578652	116618	**9695270**	**1502**	**8365768**	30049	0	**30049**	**18092590**
13	Waste, hazardous/ incinerated	g	392	3	**395**	**30**	**164340**	493900	0	**493900**	**658665**
	Emissions (Air)										
14	Greenhouse Gases in GWP100	kg CO2 ec	7002	1952	**8954**	**213**	**311406**	2603	1992	**611**	**321184**
15	Ozone Depletion, emissions	mg R-11 e				negligible					
16	Acidification, emissions	g SO2 eq.	127086	8422	**135508**	**651**	**1837864**	5184	2496	**2689**	**1976711**
17	Volatile Organic Compounds (VOC)	g	785	7	**792**	**66**	**2713**	76	34	**42**	**3613**
18	Persistent Organic Pollutants (POP)	ng i-Teq	31987	510	**32497**	**8**	**47070**	222	0	**222**	**79797**
19	Heavy Metals	mg Ni eq.	26100	1194	**27293**	**76**	**122886**	9380	0	**9380**	**159636**
	PAHs	mg Ni eq.	15721	7	**15727**	**143**	**14467**	0	1	**-1**	**30337**
20	Particulate Matter (PM, dust)	g	5459	1297	**6756**	**10927**	**43702**	44025	42	**43982**	**105367**
	Emissions (Water)										
21	Heavy Metals	mg Hg/20	8689	1	**8690**	**2**	**46070**	2943	0	**2943**	**57705**
22	Eutrophication	g PO4	319	17	**337**	**0**	**223**	168	0	**168**	**728**
23	Persistent Organic Pollutants (POP)	ng i-Teq				negligible					

Table 4-20: Life Cycle Impact (per unit) of base-case 2 – Industry oil-immersed

Figure 4-2 exposes the contribution of each life cycle phase to each impact. Several observations can be made from this analysis:

- Within the production phase, the impacts due to the manufacturing processes are very low (maximum of 2% for eutrophication). However, the extraction and production of raw material significantly contributes to some emissions, such as VOC (22%), POP (40%) or PAHs (52%), as well as to the generation of non-hazardous waste because of the high steel and copper content (53%). Core steel is the main material responsible for POP emissions while aluminium and oil induce high PAHs impacts. Eutrophication level is due to coatings, paper, core steel and copper wire.

- The use phase accounts for 97.1% of the energy consumption over the whole life cycle, 99.6% of the electricity use and 97% of the greenhouse gases emissions. These impacts are almost exclusively due to the electricity losses during the use phase, the maintenance and spare parts impacts being negligible.

- The distribution phase is negligible for all impacts except for Particulate Matter (PM) for which it accounts for around 10% of the emissions because of the transformer transportation.

- Finally, the end-of-life accounts for 75% of the hazardous waste generated, 42% of PM emissions to the air, 23% of the eutrophication impacts and 6% of heavy metals emissions. For all other impacts, it has a negligible influence. The incineration of oil is the main reason for the contributions to hazardous waste, PM and HM, even if it also reduces slightly the energy consumption over the whole life cycle because of the energy recovery process.

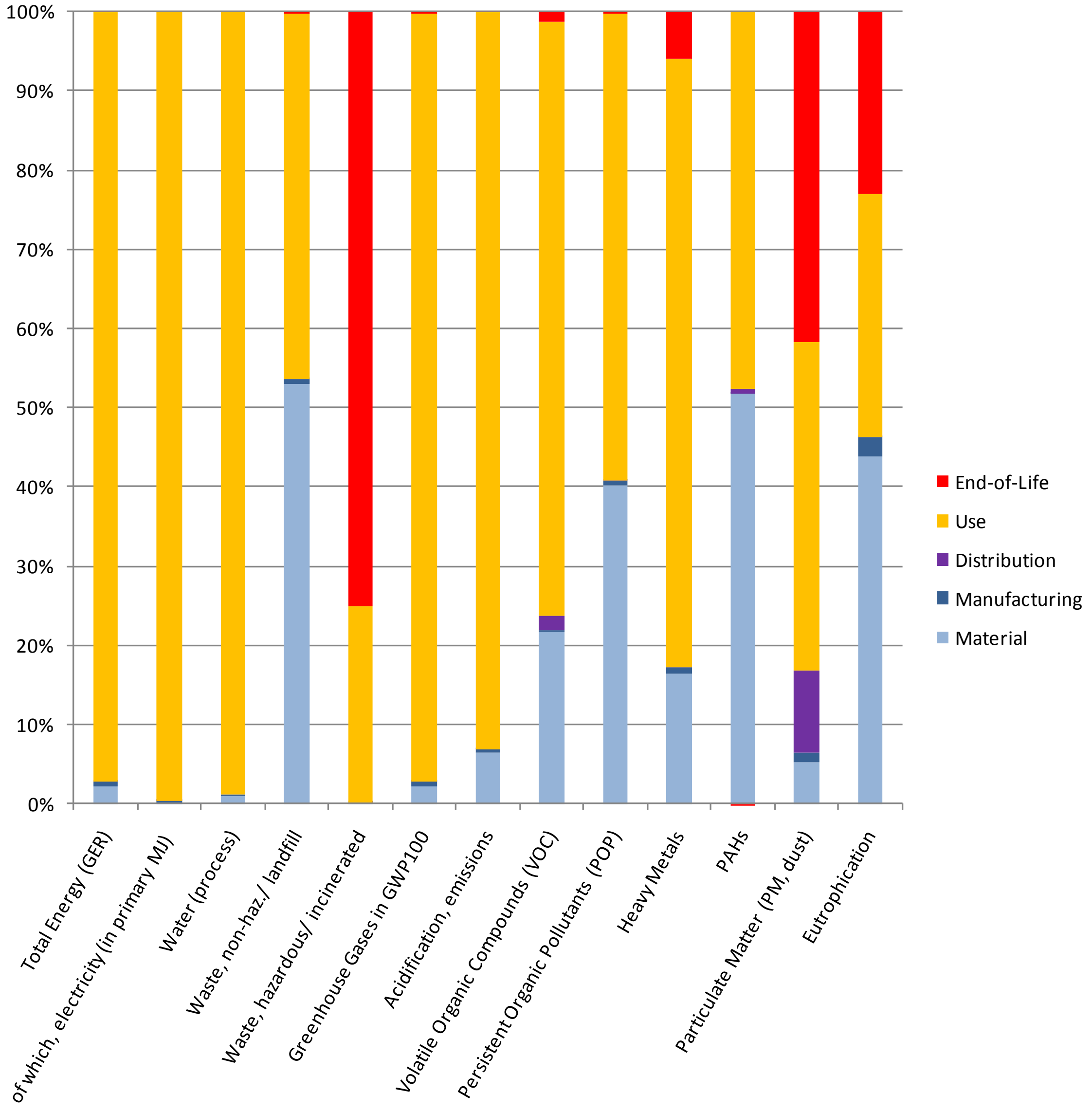


Figure 4-2: Distribution of environmental impacts of BC 2 per life cycle phase

4.3.3 Base-case 3: Industry dry transformer

Table 4-21 shows the environmental impacts of an industry dry-type transformer over its whole life cycle. For most of the 15 environmental impact indicators, the use phase is the most significant stage over the whole product life cycle. The total energy consumption for the whole life cycle of the dry-type transformer base-case is 12.83 TJ, of which 12.58 TJ (i.e. 1.2 GWh) electricity.

Nr	Life cycle Impact per product:	Date	Author
3	BC3 - Industry dry		BIO

Nr	Life Cycle phases -->		PRODUCTION			DISTRI-	USE	END-OF-LIFE*			TOTAL
	Resources Use and Emissions		Material	Manuf.	Total	BUTION		Disposal	Recycl.	Total	
	Materials	**unit**									
1	Bulk Plastics	g			**16115**			16115	0	**16115**	**0**
2	TecPlastics	g			**145958**			145958	0	**145958**	**0**
3	Ferro	g			**1991749**			45810	1945939	**1991749**	**0**
4	Non-ferro	g			**460274**			10586	449688	**460274**	**0**
5	Coating	g			**1381**			32	1350	**1381**	**0**
6	Electronics	g			**0**			0	0	**0**	**0**
7	Misc.	g			**60778**			1398	59380	**60778**	**0**
	Total weight	g			**2676256**			219900	2456356	**2676256**	**0**
									see note!		
	Other Resources & Waste							debet	credit		
8	Total Energy (GER)	MJ	218938	41670	**260608**	**3312**	**12554766**	15112	7275	**7838**	**12826523**
9	of which, electricity (in primary MJ)	MJ	8663	24830	**33493**	**8**	**12551291**	0	0	**0**	**12584792**
10	Water (process)	ltr	2854	365	**3220**	**0**	**836763**	0	0	**0**	**839982**
11	Water (cooling)	ltr	57078	11454	**68532**	**0**	**33469901**	0	0	**0**	**33538433**
12	Waste, non-haz./ landfill	g	6874155	146463	**7020617**	**1384**	**14622327**	75461	0	**75461**	**21719790**
13	Waste, hazardous/ incinerated	g	2973	7	**2980**	**27**	**289241**	162073	0	**162073**	**454321**
	Emissions (Air)										
14	Greenhouse Gases in GWP100	kg CO2 eq	10948	2327	**13275**	**196**	**547942**	1127	543	**584**	**561998**
15	Ozone Depletion, emissions	mg R-11 e					negligible				
16	Acidification, emissions	g SO2 eq.	76867	10049	**86916**	**599**	**3232833**	2236	680	**1556**	**3321905**
17	Volatile Organic Compounds (VOC)	g	307	13	**319**	**61**	**4750**	40	9	**31**	**5160**
18	Persistent Organic Pollutants (POP)	ng i-Teq	52314	1200	**53514**	**8**	**82801**	524	0	**524**	**136847**
19	Heavy Metals	mg Ni eq.	14174	2810	**16984**	**70**	**215757**	4148	0	**4148**	**236960**
	PAHs	mg Ni eq.	35114	3	**35116**	**132**	**25337**	0	0	**0**	**60585**
20	Particulate Matter (PM, dust)	g	13761	1545	**15306**	**10036**	**73593**	19207	11	**19195**	**118130**
	Emissions (Water)										
21	Heavy Metals	mg Hg/20	19967	1	**19969**	**2**	**81125**	1270	0	**1270**	**102365**
22	Eutrophication	g PO4	1567	17	**1584**	**0**	**402**	73	0	**73**	**2059**
23	Persistent Organic Pollutants (POP)	ng i-Teq					negligible				

Table 4-21: Life Cycle Impact (per unit) of base-case 3 – Industry dry-type

Figure 4-3 exposes the contribution of each life cycle phase to each impact. Several observations can be made from this analysis:

- Within the production phase, the manufacturing impacts are very small and the material extraction and production are responsible for the important contribution of this phase to the quantity of landfilled waste (32%) because of the high metal content. Also, core steel highly contributes to the important percentage of this phase in terms of POP emissions (38%) and eutrophication (76%) while aluminium results in high PAHs emissions (58%).

- As expected, the use phase is the main contributor with over 97% of all the following impacts: total energy (98%) and electricity consumption (99.7%), water for processing, greenhouse gases emissions and acidification. The smallest contributions occur for eutrophication (20%) and PAHs (42%). The electricity losses are the only reason for these impacts as the contribution of maintenance, spare parts or kilometres over product life are negligible in comparison.

- The distribution is negligible for all impacts except for Particulate Matter (PM) for which it accounts for around 8% of the emissions because of the transformer transportation.

- The end-of-life is only significant for the hazardous and incinerated waste impact (36%) because of the incineration of epoxy resign and other plastics materials during the end-of-life management. Both incineration and disposal of waste are responsible for the contribution of this phase to PM (16%) and eutrophication impacts (4%).

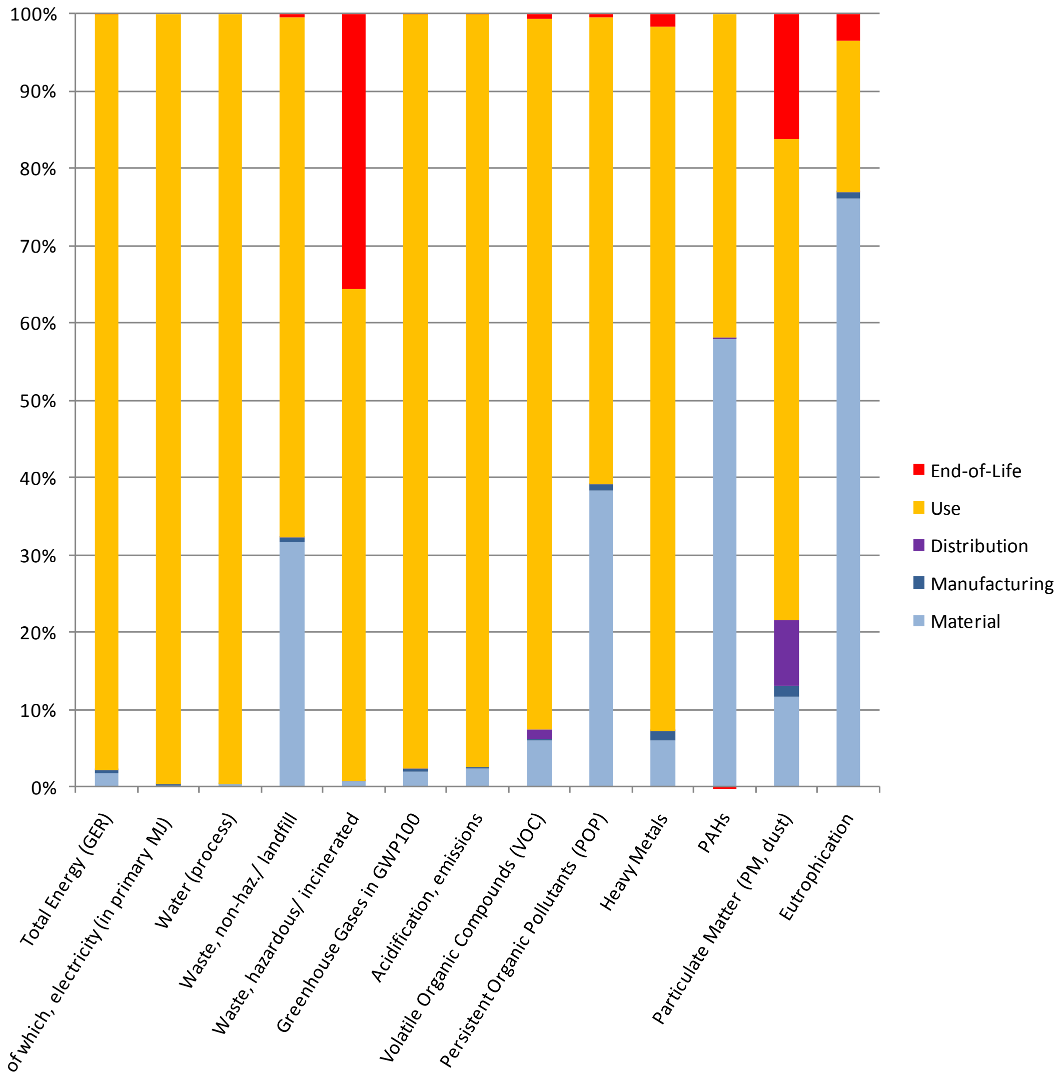


Figure 4-3: Distribution of environmental impacts of BC 3 per life cycle phase

4.3.4 Base-case 4: Power transformer

Table 4-22 shows the environmental impacts of a power transformer over its whole life cycle. The total energy consumption for the whole life cycle of the power transformer base-case is 172.9 TJ, of which 164.8 TJ (i.e. 15.7 GWh) electricity.

Nr	Life cycle Impact per product:	Date	Author
4	BC 4 - Power transformer		BIO

Nr	Life Cycle phases -->		PRODUCTION			DISTRI-	USE	END-OF-LIFE*			TOTAL
	Resources Use and Emissions		Material	Manuf.	Total	BUTION		Disposal	Recycl.	Total	
	Materials	**unit**									
1	Bulk Plastics	g			**26848483**			26848483	0	**26848483**	**0**
2	TecPlastics	g			**0**			0	0	**0**	**0**
3	Ferro	g			**50793663**			507937	50285727	**50793663**	**0**
4	Non-ferro	g			**18692588**			186926	18505662	**18692588**	**0**
5	Coating	g			**391719**			3917	387802	**391719**	**0**
6	Electronics	g			**0**			0	0	**0**	**0**
7	Misc.	g			**3649598**			36496	3613102	**3649598**	**0**
	Total weight	g			**100376052**			27583759	72792293	**100376052**	**0**
									see note!		
	Other Resources & Waste							debet	credit		
8	Total Energy (GER)	MJ	6861324	1736782	**8598106**	**209693**	**163657794**	1875349	1428242	**447107**	**172912701**
9	of which, electricity (in primary MJ)	MJ	183959	1040883	**1224842**	**536**	**163582858**	0	0	**0**	**164808235**
10	Water (process)	ltr	202252	15510	**217762**	**0**	**10906885**	0	0	**0**	**11124647**
11	Water (cooling)	ltr	335406	486265	**821671**	**0**	**436196509**	0	0	**0**	**437018179**
12	Waste, non-haz./ landfill	g	438674133	5732245	**444406377**	**85698**	**194094903**	1230550	0	**1230550**	**639817529**
13	Waste, hazardous/ incinerated	g	22240	123	**22363**	**1703**	**3769371**	26848483	0	**26848483**	**30641920**
	Emissions (Air)										
14	Greenhouse Gases in GWP100	kg CO2 eq	280136	96643	**376779**	**12325**	**7141991**	139829	106586	**33243**	**7564338**
15	Ozone Depletion, emissions	mg R-11 eq				negligible					
16	Acidification, emissions	g SO2 eq.	5912437	416946	**6329384**	**37764**	**42182819**	278522	133513	**145010**	**48694976**
17	Volatile Organic Compounds (VOC)	g	42491	299	**42790**	**3895**	**62052**	4059	1845	**2215**	**110952**
18	Persistent Organic Pollutants (POP)	ng i-Teq	1247602	21907	**1269509**	**484**	**1084832**	9276	0	**9276**	**2364102**
19	Heavy Metals	mg Ni eq.	1231381	51317	**1282698**	**4345**	**2819342**	503348	0	**503348**	**4609733**
	PAHs	mg Ni eq.	643387	352	**643738**	**8307**	**328933**	0	38	**-38**	**980941**
20	Particulate Matter (PM, dust)	g	190254	64222	**254476**	**645196**	**906593**	2363947	2256	**2361691**	**4167955**
	Emissions (Water)										
21	Heavy Metals	mg Hg/20	316611	27	**316638**	**136**	**1057821**	158130	0	**158130**	**1532725**
22	Eutrophication	g PO4	12313	884	**13197**	**2**	**5161**	9040	0	**9040**	**27401**
23	Persistent Organic Pollutants (POP)	ng i-Teq				negligible					

Table 4-22: Life Cycle Impact (per unit) of base-case 4 – Power

Figure 4-4 exposes the contribution of each life cycle phase to each impact. Several observations can be made from this analysis:

- Within the production phase, the impacts due to the manufacturing processes are very low (maximum of 3% for eutrophication). However, the extraction and production of raw material significantly contributes to some emissions, such as VOC (38%), POP (53%) or PAHs (66%), as well as to the generation of non-hazardous waste because of the high steel and copper content (69%). Core steel is the main material responsible for POP emissions while mineral oil results in high levels of VOC and PAHs.

- The use phase is overwhelming for energy (95%) and electricity (99.3%) consumption, which is again only due the electricity losses during the lifetime and not to maintenance or spare parts. In terms of emissions, its contribution varies between 22% for PM and 94% for GWP, and also represents around 46% of POP and 61% of HM emissions.

- The distribution phase is negligible for all impacts except for PM for which it accounts for around 15% of the emissions because of the transformer transportation.

- Finally, the end-of-life accounts for 88% of the hazardous waste generated, 57% of PM emissions to the air, 33% of the eutrophication impacts and 11% of heavy metals emissions. For all other impacts, it has a negligible influence. The incineration of oil is the main reason for the high contributions to hazardous waste, PM and HM, even if it also reduces slightly the energy consumption over the whole life cycle because of the energy recovery process.

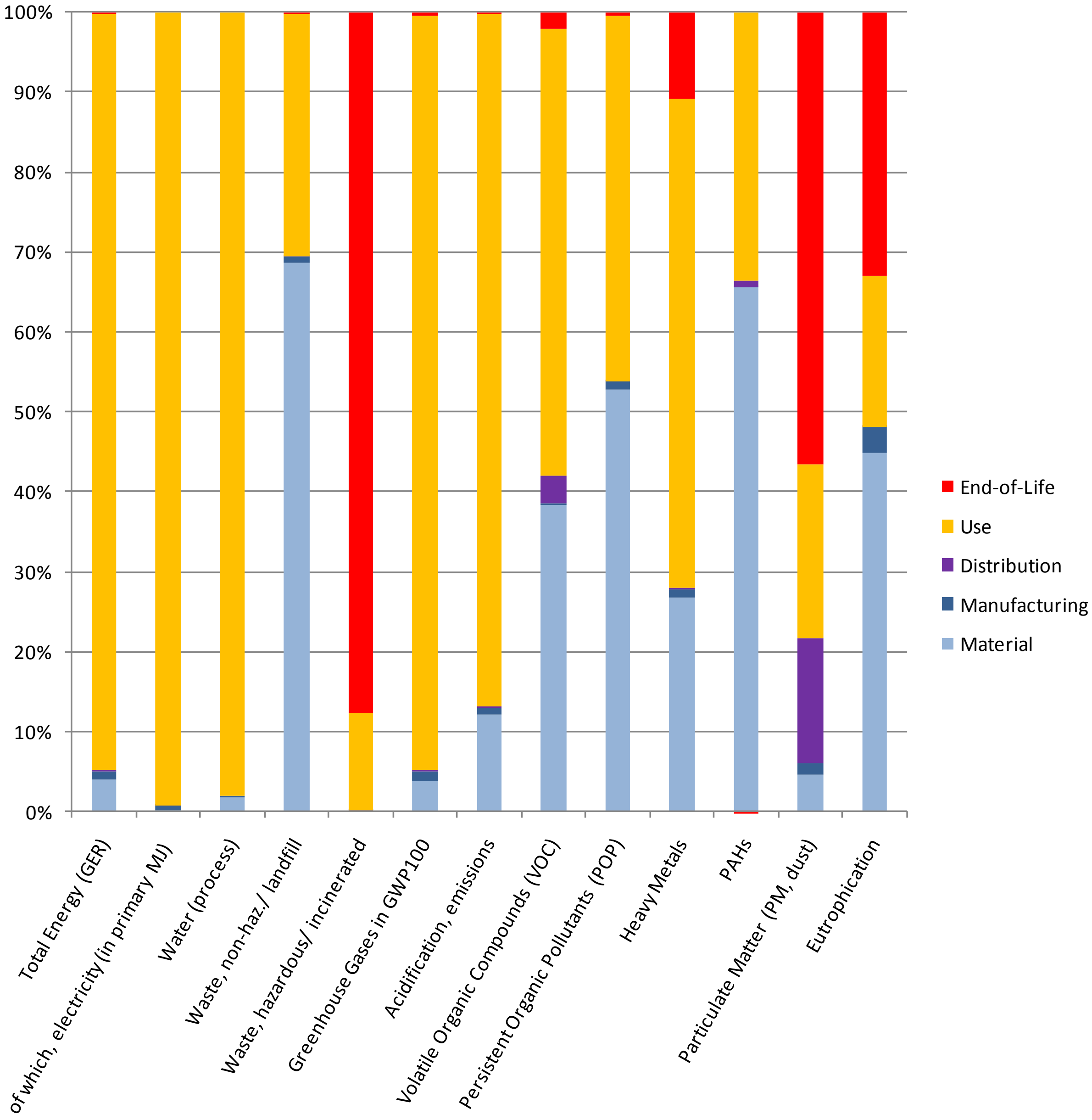


Figure 4-4: Distribution of environmental impacts of BC 4 per life cycle phase

4.3.5 Base-case 5: DER oil transformer

Table 4-23 shows the environmental impacts of DER oil-immersed transformer over its whole life cycle. The total energy consumption for the whole life cycle of the oil-immersed DER transformer base-case is 15.9 TJ, of which 15.6 TJ (i.e. 1.5 GWh) electricity.

Nr	Life cycle Impact per product:	Date	Author
5	BC 5 - DER (oil-immersed)	0	BIO

	Life Cycle phases -->		PRODUCTION			DISTRI-	USE	END-OF-LIFE*			TOTAL
	Resources Use and Emissions		Material	Manuf.	Total	BUTION		Disposal	Recycl.	Total	
	Materials	**unit**									
1	Bulk Plastics	g			**800304**			800304	0	**800304**	**0**
2	TecPlastics	g			**21687**			21687	0	**21687**	**0**
3	Ferro	g			**2828476**			28285	2800191	**2828476**	**0**
4	Non-ferro	g			**952177**			9522	942655	**952177**	**0**
5	Coating	g			**4321**			43	4278	**4321**	**0**
6	Electronics	g			**0**			0	0	**0**	**0**
7	Misc.	g			**20924**			209	20714	**20924**	**0**
	Total weight	g			**4627889**			860050	3767839	**4627889**	**0**
									see note!		
	Other Resources & Waste							debet	credit		
8	Total Energy (GER)	MJ	308592	67000	**375592**	**4511**	**15517003**	58478	43132	**15345**	**15912451**
9	of which, electricity (in primary MJ)	MJ	11353	40090	**51444**	**11**	**15512558**	0	0	**0**	**15564014**
10	Water (process)	ltr	9912	595	**10507**	**0**	**1034241**	0	0	**0**	**1044749**
11	Water (cooling)	ltr	30120	18664	**48785**	**0**	**41365938**	0	0	**0**	**41414722**
12	Waste, non-haz./ landfill	g	17280452	225093	**17505545**	**1873**	**18160390**	56735	0	**56735**	**35724543**
13	Waste, hazardous/ incinerated	g	1123	6	**1130**	**37**	**357454**	821991	0	**821991**	**1180613**
	Emissions (Air)										
14	Greenhouse Gases in GWP100	kg CO2 eq.	13690	3732	**17422**	**267**	**677204**	4360	3219	**1141**	**696034**
15	Ozone Depletion, emissions	mg R-11 eq.	negligible								
16	Acidification, emissions	g SO2 eq.	215639	16105	**231744**	**815**	**3996762**	8683	4032	**4651**	**4233971**
17	Volatile Organic Compounds (VOC)	g	1325	14	**1339**	**83**	**5875**	129	56	**73**	**7370**
18	Persistent Organic Pollutants (POP)	ng i-Teq	63414	1144	**64558**	**11**	**102321**	415	0	**415**	**167304**
19	Heavy Metals	mg Ni eq.	48508	2680	**51188**	**95**	**266900**	15721	0	**15721**	**333904**
	PAHs	mg Ni eq.	34725	11	**34736**	**179**	**31166**	0	1	**-1**	**66080**
20	Particulate Matter (PM, dust)	g	11981	2480	**14461**	**13724**	**89871**	73757	68	**73689**	**191745**
	Emissions (Water)										
21	Heavy Metals	mg Hg/20	30268	1	**30269**	**3**	**100320**	4930	0	**4930**	**135522**
22	Eutrophication	g PO4	619	32	**651**	**0**	**483**	282	0	**282**	**1417**
23	Persistent Organic Pollutants (POP)	ng i-Teq	negligible								

Table 4-23: Life Cycle Impact (per unit) of base-case 5 – DER (oil)

Figure 4-5 exposes the contribution of each life cycle phase to each impact. Several observations can be made from this analysis:

- Within the production phase, the impacts due to the manufacturing processes are very low (maximum of 2% for eutrophication). However, the extraction and production of raw material significantly contributes to some emissions, such as VOC (18%), POP (38%) or PAHs (53%), as well as to the generation of non-hazardous waste because of the high steel and copper content (48%). Core steel is the main material responsible for POP emissions while mineral oil and aluminium induce high PAHs impacts.

- The use phase accounts for 97.5% of the energy consumption over the whole life cycle, 99.7% of the electricity use and 97% of the greenhouse gases emissions. These impacts are almost exclusively due to the electricity losses during the use phase.

- The distribution phase is negligible for all impacts except for PM for which it accounts for around 7% of the emissions because of the transformer transportation.

- Finally, the end-of-life accounts for 70% of the hazardous waste generated, 38% of PM emissions to the air, 20% of the eutrophication impacts and 5% of heavy metals emissions. For all other impacts, it has a negligible influence. The incineration of oil is the main reason for the contributions to hazardous waste, PM and HM, even if it also reduces slightly the energy consumption over the whole life cycle because of the energy recovery process.

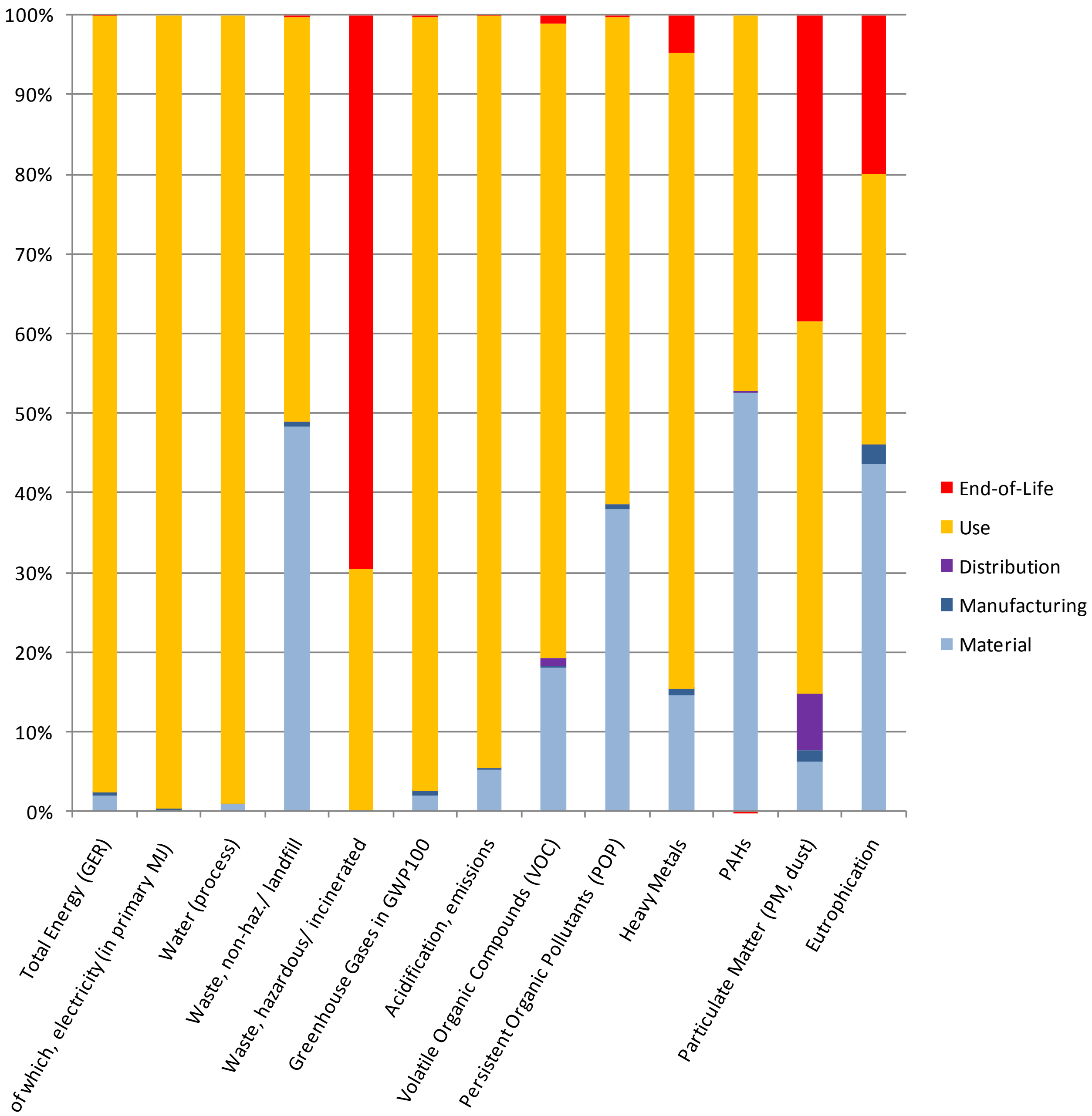


Figure 4-5: Distribution of environmental impacts of BC 5 per life cycle phase

4.3.6 Base-case 6: DER dry transformer

Table 4-24 shows the environmental impacts of DER dry-type transformer over its whole life cycle. The total energy consumption for the whole life cycle of the dry-type DER transformer base-case is 16.9 TJ, of which 16.4 TJ (i.e. 1.56 GWh) electricity.

Nr	Life cycle Impact per product:	Date	Author
6	BC 6 - DER dry transformer		BIO

Nr	Life Cycle phases -->		PRODUCTION			DISTRI-	USE	END-OF-LIFE*			TOTAL
	Resources Use and Emissions		Material	Manuf.	Total	BUTION		Disposal	Recycl.	Total	
	Materials	**unit**									
1	Bulk Plastics	g			59900			59900	0	59900	0
2	TecPlastics	g			112514			112514	0	112514	0
3	Ferro	g			3984468			167348	3817121	3984468	0
4	Non-ferro	g			841004			35322	805682	841004	0
5	Coating	g			5556			233	5323	5556	0
6	Electronics	g			0			0	0	0	0
7	Misc.	g			221425			9300	212125	221425	0
	Total weight	g			5224867			384617	4840250	5224867	0
									see note!		
	Other Resources & Waste							debet	credit		
8	Total Energy (GER)	MJ	406397	76403	482801	4788	16389969	26596	8474	18121	16895678
9	of which, electricity (in primary MJ)	MJ	13813	45489	59302	12	16384531	0	0	0	16443845
10	Water (process)	ltr	2447	668	3115	0	1092294	0	0	0	1095409
11	Water (cooling)	ltr	47196	20946	68142	0	43691181	0	0	0	43759323
12	Waste, non-haz./ landfill	g	9824108	270853	10094961	1986	19097195	269026	0	269026	29463169
13	Waste, hazardous/ incinerated	g	2579	13	2592	39	377560	172414	0	172414	552605
	Emissions (Air)										
14	Greenhouse Gases in GWP100	kg CO2 eq.	20396	4269	24665	283	715326	1984	632	1352	741625
15	Ozone Depletion, emissions	mg R-11 eq.				negligible					
16	Acidification, emissions	g SO2 eq.	90716	18437	109153	865	4220048	3919	792	3126	4333193
17	Volatile Organic Compounds (VOC)	g	631	24	655	88	6197	86	11	75	7015
18	Persistent Organic Pollutants (POP)	ng i-Teq	101979	2374	104353	11	108433	1856	0	1856	214653
19	Heavy Metals	mg Ni eq.	16823	5561	22384	101	281570	7492	0	7492	311548
	PAHs	mg Ni eq.	81716	4	81720	190	33354	0	0	0	115264
20	Particulate Matter (PM, dust)	g	26189	2835	29024	14576	94812	34128	13	34114	172526
	Emissions (Water)										
21	Heavy Metals	mg Hg/20	42781	3	42784	3	106067	2225	0	2225	151078
22	Eutrophication	g PO4	1394	30	1424	0	518	127	0	127	2070
23	Persistent Organic Pollutants (POP)	ng i-Teq				negligible					

Table 4-24: Life Cycle Impact (per unit) of base-case 6 – DER (dry)

Figure 4-6 exposes the contribution of each life cycle phase to each impact. Several observations can be made from this analysis:

- Within the production phase, the manufacturing impacts are very small: the maximum contribution is 2% in HM emissions, because of the sheetmetal scrap generated during the manufacturing. The material extraction and production are responsible for the important contribution of this phase to the quantity of landfilled waste (33%) because of the high aluminium and core steel content. Also, core steel highly contributes to the important percentage of this phase in terms of POP emissions (48%) and eutrophication (67%) while aluminium results in high PAHs emissions (71%). Also, the VOC emissions (around 9% contribution of the production phase) are mainly the consequence of the production of ceramics.

- As expected, the use phase is the main contributor to the following impacts: total energy (97%) and electricity consumption (99.6%), water for processing, greenhouse gases emissions (96.5%) and acidification (97.4%). The smallest contributions occur for eutrophication and PAHs (25% and 29%). The electricity losses are the only reason for these impacts as the contribution of maintenance, spare parts or kilometres over product life are negligible in comparison.

- The distribution is negligible for all impacts except for PM for which it accounts for around 8% of the emissions because of the transformer transportation. It also represents 1% of the VOC emissions.

- The end-of-life is only significant for the hazardous and incinerated waste impact (31%) because of the incineration of epoxy resin and other plastics materials during the end-of-life management. Both incineration and disposal of waste are responsible for the contribution of this phase to PM (20%) and eutrophication impacts (6%).

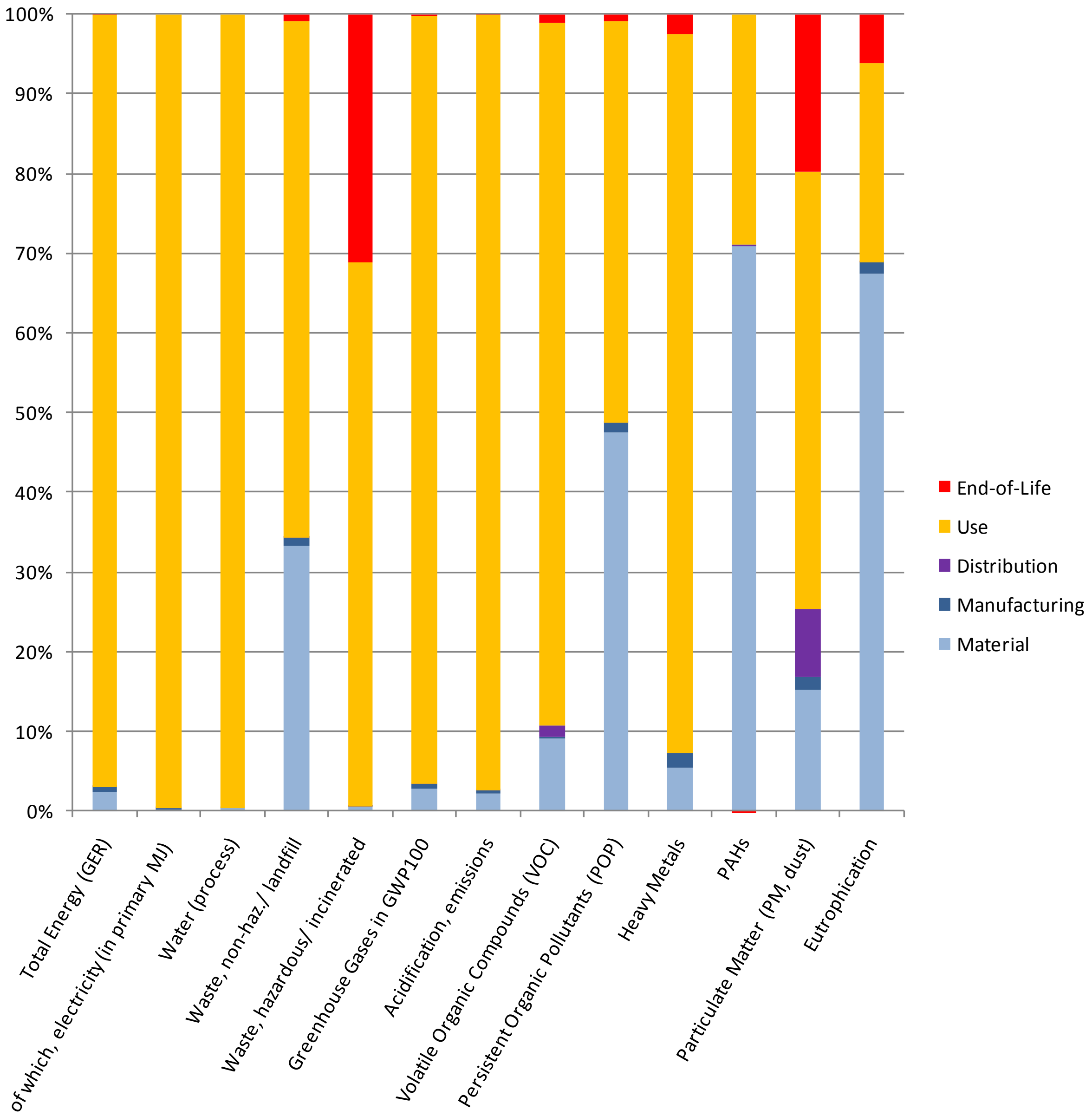


Figure 4-6: Distribution of environmental impacts of BC 6 per life cycle phase

4.3.7 Base-case 7: Separation/isolation transformer

Table 4-25 shows the environmental impacts of separation/isolation transformer over its whole life cycle. The total energy consumption for the whole life cycle of the separation/isolation transformer base-case is 63.1 GJ, of which 53.6 GJ (i.e. 5.1 MWh) electricity.

Nr	Life cycle Impact per product:	Date	Author
7	BC 7 - Separation/isolation		BIO

Nr	Life Cycle phases -->		PRODUCTION			DISTRI-	USE	END-OF-LIFE*			TOTAL
	Resources Use and Emissions		Material	Manuf.	Total	BUTION		Disposal	Recycl.	Total	
	Materials	**unit**									
1	Bulk Plastics	g			**0**			0	0	**0**	**0**
2	TecPlastics	g			**0**			0	0	**0**	**0**
3	Ferro	g			**50000**			500	49500	**50000**	**0**
4	Non-ferro	g			**35000**			350	34650	**35000**	**0**
5	Coating	g			**0**			0	0	**0**	**0**
6	Electronics	g			**0**			0	0	**0**	**0**
7	Misc.	g			**0**			0	0	**0**	**0**
	Total weight	g			**85000**			850	84150	**85000**	**0**
									see note!		
	Other Resources & Waste							debet	credit		
8	Total Energy (GER)	MJ	7915	786	**8702**	**98**	**54263**	58	4	**54**	**63117**
9	of which, electricity (in primary MJ)	MJ	114	468	**582**	**0**	**52979**	0	0	**0**	**53560**
10	Water (process)	ltr	0	7	**7**	**0**	**3532**	0	0	**0**	**3538**
11	Water (cooling)	ltr	0	215	**215**	**0**	**141263**	0	0	**0**	**141478**
12	Waste, non-haz./ landfill	g	787476	2821	**790297**	**70**	**69322**	1042	0	**1042**	**860731**
13	Waste, hazardous/ incinerated	g	28	0	**28**	**1**	**1221**	0	0	**0**	**1250**
	Emissions (Air)										
14	Greenhouse Gases in GWP100	kg CO2 eq.	399	44	**443**	**7**	**2409**	4	0	**4**	**2864**
15	Ozone Depletion, emissions	mg R-11 eq.				negligible					
16	Acidification, emissions	g SO2 eq.	11007	190	**11197**	**20**	**13845**	9	0	**8**	**25071**
17	Volatile Organic Compounds (VOC)	g	8	0	**8**	**1**	**39**	0	0	**0**	**49**
18	Persistent Organic Pollutants (POP)	ng i-Teq	1439	27	**1466**	**0**	**362**	7	0	**7**	**1835**
19	Heavy Metals	mg Ni eq.	2155	63	**2218**	**4**	**1191**	17	0	**17**	**3430**
	PAHs	mg Ni eq.	197	0	**197**	**4**	**366**	0	0	**0**	**568**
20	Particulate Matter (PM, dust)	g	241	29	**270**	**144**	**4704**	76	0	**76**	**5194**
	Emissions (Water)										
21	Heavy Metals	mg Hg/20	404	0	**404**	**0**	**346**	5	0	**5**	**754**
22	Eutrophication	g PO4	9	0	**9**	**0**	**2**	0	0	**0**	**11**
23	Persistent Organic Pollutants (POP)	ng i-Teq				negligible					

Table 4-25: Life Cycle Impact (per unit) of base-case 7 – separation/isolation

Figure 4-7 exposes the contribution of each life cycle phase to each impact. Several observations can be made from this analysis:

- Within the production phase, the manufacturing impacts are very small: the maximum contribution is 3% in eutrophication, because of the sheetmetal scrap generated during the manufacturing. The material extraction and production are responsible for the important contribution of this phase to the quantity of landfilled waste (91%) and eutrophication potential (79%) because of the aluminium and core steel content. Also, core steel highly contributes to the important percentage of this phase in terms of POP emissions (78%) while PAHs (35%), HM (63%) and acidification (44%) impacts are mainly due to the copper.

- As expected, the use phase is the main contributor to the following impacts: total energy (86%) and electricity consumption (98.9%), water for processing (99.8%), greenhouse gases emissions (84%) and particulate matter (91%). The smallest contributions occur for eutrophication (16%), POPs emissions (20%) and generation of non-hazardous waste (8%). The electricity losses are the main reason for these impacts.

- The distribution is negligible for all impacts except for PM for which it accounts for around 2.8% of the emissions because of the transformer transportation. It also represents 1.9% of the VOC emissions.

- The end-of-life is also negligible for all impacts except for eutrophication (2.5%) and PM (1.5%). As only metal components are present in the BOM, no material is incinerated (like resin or oil for the other base-cases). Besides, the disposal percentage is low (assumed to be 1%) which explains the low impacts of this life cycle phase.

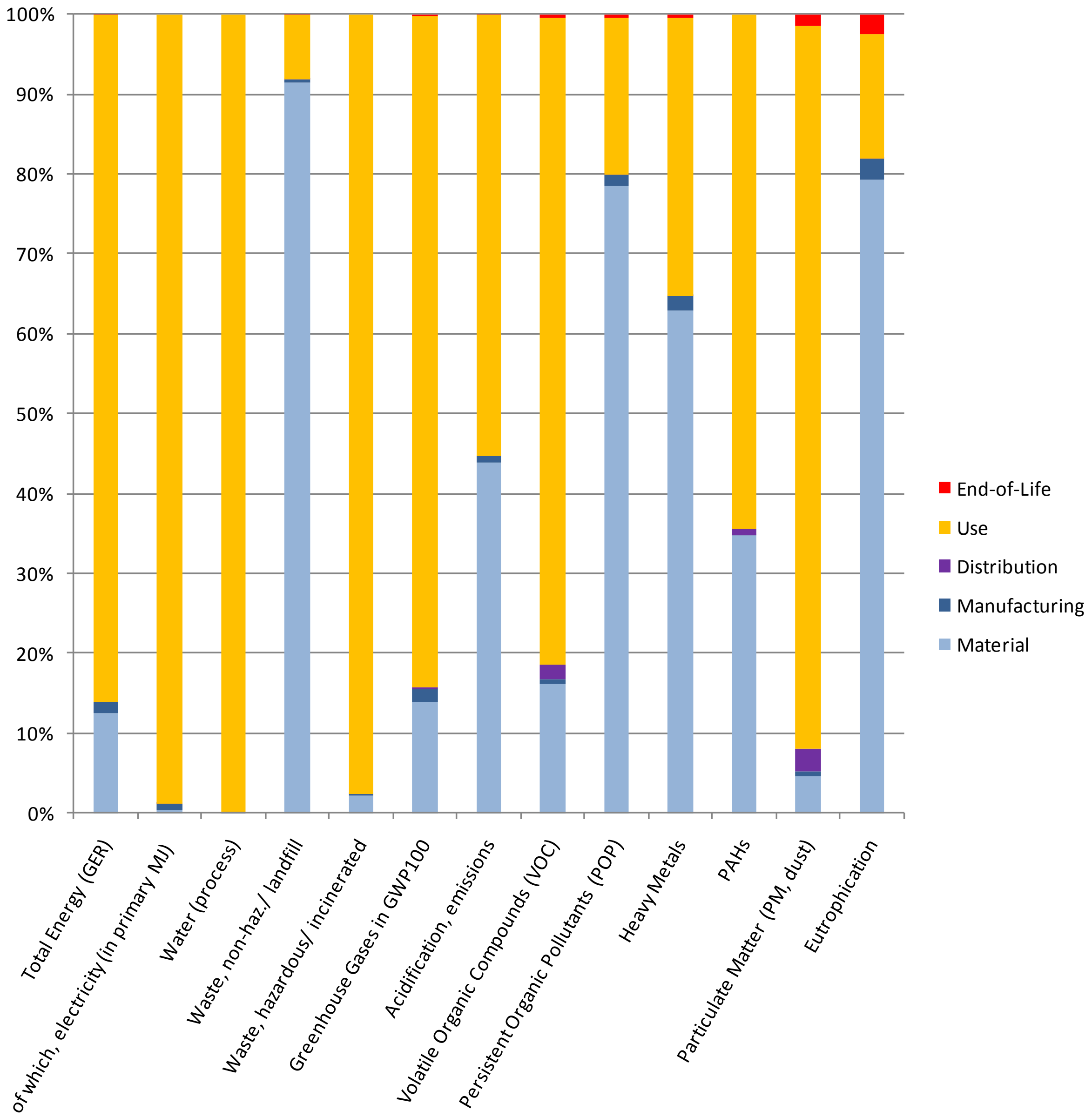


Figure 4-7: Distribution of environmental impacts of BC 7 per life cycle phase

4.3.8 Comparison with other LCAs and conclusions

According to the Transformer Handbook (ABB[100]), environmental impacts due to raw materials extraction, manufacturing and distribution are negligible compared to energy losses during service. Besides, raw material extraction impacts are balanced by the high recycling rate.

The results of the impact assessment of the seven base-cases are in line with this analysis regarding energy and electricity consumption, and greenhouse gases emissions: the use phase always represents more than 94% of these impacts ("only" 86% of total energy for BC7, because of the shorter lifetime considered). Furthermore, the only contributor within the use phase is the electricity consumption (losses) as maintenance or spare parts are negligible.

The main components having an important influence on the environmental impacts are the metal materials, which increase the contribution of the material section to PAHs and POP emissions as well as to the quantity of non-hazardous waste.

In oil-immersed transformers, mineral oil contributes through the end-of-life phase as it is considered 100% incinerated and is found in significant quantity: it results in higher VOC and PAHs emissions and above all more generation of hazardous waste. However, the quantity of hazardous waste is not a fundamental impact in the analysis as the impacts of incineration are already taken into accounts in all the emissions. The same is valid for the generation of non-hazardous waste. The thermal recycling process also slightly reduces the total energy consumption over the life cycle: in this project, the credits from energy recovery by oil incineration are expected to be underestimated as the default parameters of plastics incineration (instead of accurate figures on oil incineration) were used because of data limitations. Thus, the overall contribution of mineral oil to the environmental impacts may be slightly overestimated.

In dry-type transformers, epoxy resin, plastics and nomex® are also incinerated during the end-of-life management, and have similar effects as mineral oil.

Because the impacts of mineral oil and ceramics were calculated and not contained initially in the EcoReport database, the conclusions about the influence of these materials have to be taken with caution.

4.4 Base-Case Life Cycle Costs

The result of the procurement process should be the cheapest transformer, having the lowest total cost of ownership, taking into account the losses and optimised for a given application.

4.4.1 EcoReport analysis

Economic data used for the calculations of the Life Cycle Costs (LCC) were partly elaborated in Chapter 2 (product lifetime and electricity rates). The discount rate was provided by the EC and is the same for all base-cases. For distribution and industry-oil transformers, the overall improvement ratios (market over stock) were calculated from data in SEEDT while the other ratios were assumed to be 1. For each base-case, this improvement ratio indicates the difference of global efficiency between the new sales and the current stock. The product prices were estimated with the data aggregation

[100] ABB Transformer Handbook (2007), 3rd edition.

used for the definition of the base-cases and based on the stakeholders' enquiries and literature review.

Table 4-26 presents the summary of the LCC input data and results for the 7 base-cases.

Input	***BC1 Distribution***	***BC2 Industry oil***	***BC3 Industry dry***	***BC4 Power***	***BC5 DER oil***	***BC6 DER dry***	***BC7 Separation /isolation***
Lifetime *(years)*	40	25	30	30	25	25	10
Electricity rate *(€/kWh)*	0.078				0.3		0.078
Discount rate	4%						
Overall Improvement ratio	1.0039	1.0001	1	1	1	1	1
Product price *(€)*	6 122	10 926	16 333	755 843	18 248	28 192	1 348
Electricity cost *(€)*	12 133	33 105	53 741	700 383	276 949	292 516	319
Life Cycle Cost *(€)*	18 255	44 031	70 074	1 456 226	295 197	320 707	1 667

Table 4-26: EcoReport inputs and outcomes of the LCC calculations of the seven base-cases

The installation costs and repair/maintenance costs were neglected in this analysis because of a lack of data. Thus, it is assumed that the variation of these costs between two different transformers is negligible in comparison with the product price and electricity cost as the maintenance of more efficient products should not be affected by the details of the core material or windings.

Figure 4-8 shows the contribution of the product price and the electricity costs for the seven base-cases LCC. For distribution and power transformers, the product price represents 34% and 52% of the global LCC. For industry transformers, both dry-type and oil-immersed, the product price only accounts for around 25% and gets an even smaller share for DER transformers (6% for oil-immersed DER and 9% for dry-type ones). Finally, small separation and isolation transformers show the largest share for the product price (81%) which can be explained by the low availability factor and the shorter lifetime considered. It reduces the time during which these transformers are used, and thus the losses.

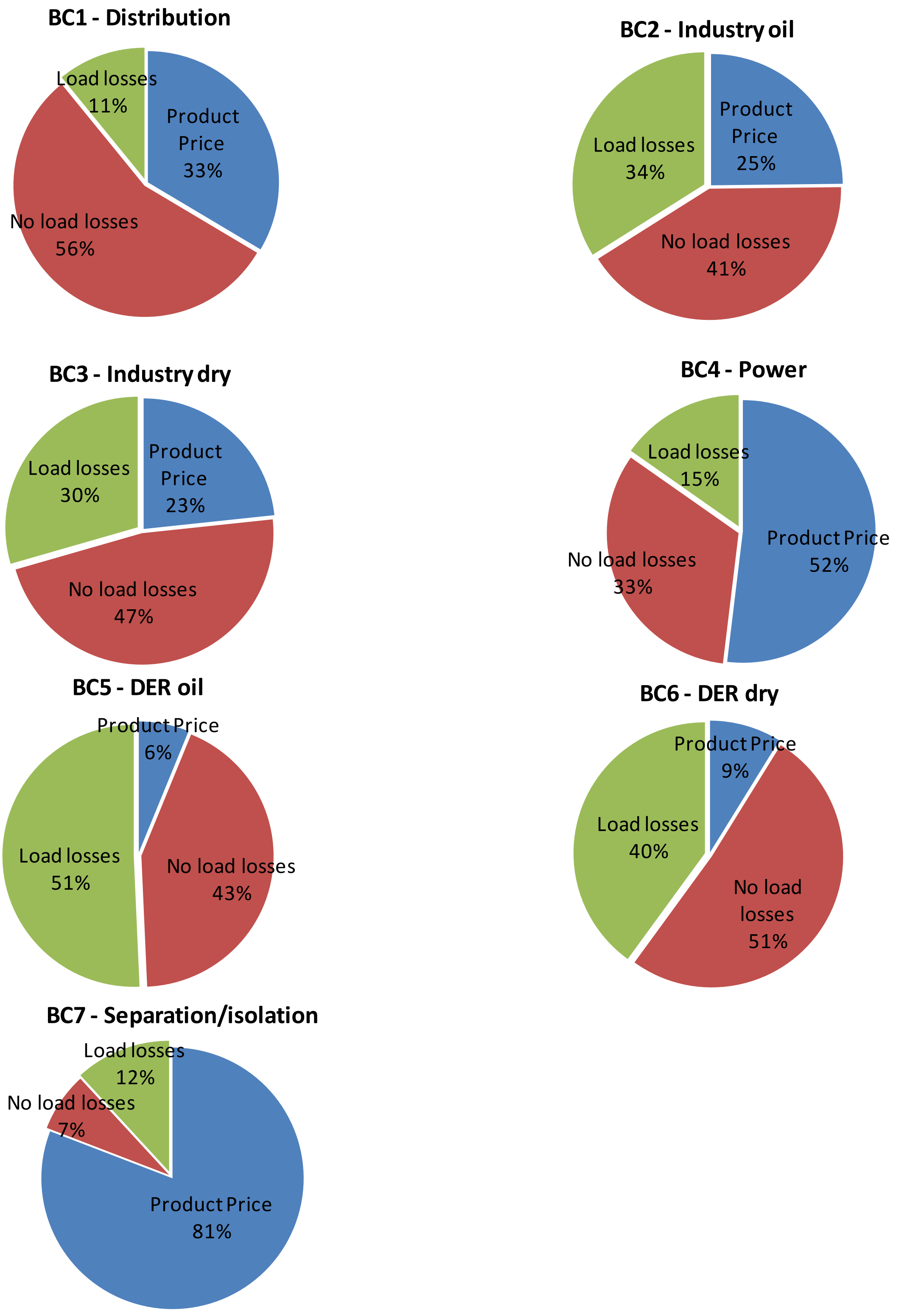


Figure 4-8: Base-cases' share of the LCC

4.4.2 Specific TCO

Specific Total Cost of Ownership (TCO) (see Chapter 3) can be calculated by summarising the cost of the transformer and the costs of losses, using the formulas given in the HD 428 and HD 538[101]. The calculations made with this method were used to check the consistency of the EcoReport outcomes on the LCC analysis:

$$TCO = PP + A*P_0 + B*P_k$$

With: PP = Purchase Price
A = cost of no-load losses per Watt
P_0 = rated no-load loss
B = cost of load losses per Watt
P_k = rated load loss

A and B can be determined by the following expressions:

$$A = \frac{(1+i)^n - 1}{i*(1+i)^n} * C_{kWh} * 8760 \qquad B = A*(\frac{I_l}{I_r})^2$$

With: i = interest rate (%/year)
n = lifetime (years)
C_{kWh} = kWh price (€/kWh)
8 760 = number of hours in a year (h/year)
I_l = loading current (A)
I_r = rated current (A)

The uncertainties on the values of A and B are relatively high as it is difficult to assess the expected loading of the transformer and the electricity price. Table 4-27 exposes the inputs and outcomes of these calculations.

[101] SEEDT report, 'Selecting energy efficient distribution transformers – a guide for achieving least-cost solutions' Project No. EIE/05/056/SI2.419632, June 2008, prepared for the Intelligent Energy Europe Programme by the Polish Copper Promotion Centre and European Copper Institute.

	BC1 Distribution	BC2 Industry oil	BC3 Industry dry	BC4 Power	BC5 DER oil	BC6 DER dry	BC7 Separation /isolation
Inputs							
Lifetime *[years]*	40	25	30	30	25	25	10
Electricity rate *[€/kWh]*	0.078				0.3		0.078
Interest rate	4% (provided by the EC, same as in discount rate)						
Loading factor: I_l / I_r	0.15	0.3	0.3	0.2	0.25	0.25	0.4
Outcomes							
A *[€/W]*	13.52	10.67	11.82	11.82	41.05	41.05	5.54
B *[€/W]*	0.30	0.96	1.06	0.47	2.57	2.57	0.89
Purchase Price *[€]*	6 122	10 926	16 333	755 843	18 248	28 192	1 348
TCO *[€]*	17 665	39 160	63 346	1 388 434	199 403	238 598	2 623
EcoReport LCC[102] [€]	18 255	44 031	70 074	1 456 226	295 197	320 707	1 667
(LCC-TCO)/TCO	3.3%	12.4%	10.6%	4.9%	48.0%	34.4%	-36.4%

Table 4-27: Inputs for calculations of parameters A and B and TCO results

First of all, the TCO formula does not take the availability factor into account whereas it is taken into account in the EcoReport LCC, via the electricity losses that are calculated according to Formula 3.2 (see Task 3). Consequently, the TCO does not seem applicable to the cases where transformers are temporarily switched off (BC 5, 6 & 7), which justifies the important differences between the LCC and the TCO for these base-cases.

The second difference only lies in the Formula 3.2:

$$Etr(y)\ [kWh] = Af \times (P_o[W] + P_k[W] \times (\alpha \times K_f/PF)^2 + P_{aux}) \times 8\,760/1\,000$$

If the term $(\alpha \times K_f/PF)^2$ was replaced by a simpler evaluation of the square loading, i.e. simply α^2, the two formulas would give exactly the same outcomes (for base-cases with availability factors of 1). Indeed, both methods take into account the capitalisation of losses with a similar manner as a Present Worth Factor (PWF) is used in the EcoReport LCC formula:

$$PWF = 1/i - 1/(i.(1+i)^n)$$

With: i = discount rate (%/year)

[102] Results taken from previous section.

n = lifetime (years)

This exact term can be found in the calculation of the A and B factors of the TCO, as:
- A = "PWF" * C_{kWh} * 8760;
- B = A * α^2.

Despite this small formula difference, for BC 1 to 4, the outcomes of this specific TCO formula are relatively close to the EcoReport results and the difference between these two methods is comprised between 12.4% for BC 2 and 3.3% for BC 1. These two calculations are also very sensitive to the discount rate (for LCC) and the interest rate (for TCO) and the sensitivity analysis in Chapter 6 will take this into account. This leads to the conclusion that the EcoReport LCC method is applicable to power and distribution transformers. The results given by the EcoReport are thus considered relevant and will be used for the economic analysis in the following sections.

4.5 EU Totals

This section provides the environmental assessment of the base-cases at the EU-27 level using stock and market data from chapter 2. The reference year for the EU totals is 2005 for environmental impacts. The total impacts cover:
- The life cycle environmental impact of the new products in 2005 (this relates to a period of 2005 up to 2005 + product life) (i.e. impacts of the sales)
- The annual (2005) impact of production, use and disposal of the product group, assuming post RoHS and post-WEEE condition and the total LCC (i.e. impact and LCC of the stock)

4.5.1 Market data for all sectors

Table 4-28 displays the market data of the seven base-cases in EU-27 in 2005. Because there has been a trend to increase the size of transformers in the past 30 years, the figures of the stock given in chapter 2 correspond to smaller transformers than the base-cases in terms of power rating (for BC 1-2-3 only). Thus corrected stock figures have been introduced in order to keep a constant global capacity between the actual situation, and the virtual situation where all the stock transformers correspond to the base-case rating. The following formula was used:

$$\text{Corrected stock} \times S_{bc} = \text{Actual stock} \times S_{avg}$$

Where S_{bc} is the rating power of the base-case
S_{avg} is the rating power of average transformer in stock

In particular:
- the average distribution transformer in the current stock has a rating power of 250 kVA while the base-case 1 is defined as 400 kVA. The correction factor is 0.625.
- the average industry-oil transformer in the current stock has a rating power of 630 kVA while the base-case 2 is defined as 1 000 kVA. The correction factor is 0.63.
- the average industry-dry transformer in the current stock has a rating power of 800 kVA while the base-case 1 is defined as 1 250 kVA. The correction factor is 0.64.

Thus, the figures presented in Table 4-28 include both real stock and corrected stock figures. The corrected figures will be used as inputs for the analysis carried out in this project.

<table>
<tr><th>Input</th><th>BC1 Distribution</th><th>BC2 Industry oil</th><th>BC3 Industry dry</th><th>BC4 Power</th><th>BC5 DER oil</th><th>BC6 DER dry</th><th>BC7 Separation /isolation</th></tr>
<tr><td>Lifetime (years)</td><td>40</td><td>25</td><td>30</td><td>30</td><td>25</td><td>25</td><td>10</td></tr>
<tr><td>EU Stock 2005</td><td>3 600 000</td><td>800 000</td><td>170 000</td><td rowspan="2">64 350</td><td rowspan="2">4 000</td><td rowspan="2">16 000</td><td rowspan="2">750 000</td></tr>
<tr><td>Corrected EU Stock 2005 (units)</td><td>2 250 000</td><td>504 000</td><td>108 800</td></tr>
<tr><td>Annual sales (units/year)</td><td>140 400</td><td>43 200</td><td>8 047</td><td>3 046</td><td>580</td><td>2 320</td><td>75 000</td></tr>
</table>

Table 4-28: Market and technical data for all base-cases in 2005

4.5.2 Life Cycle Environmental Impacts

Table 4-29 shows the total environmental impacts of all products in operation in EU-27 in 2005, based on the extrapolation of the base-cases impacts (all transformers have the same impacts as the base-case of their category). These figures come from the EcoReport tool by multiplying the individual environmental impacts of a base-case with the stock of this base-case in 2005.

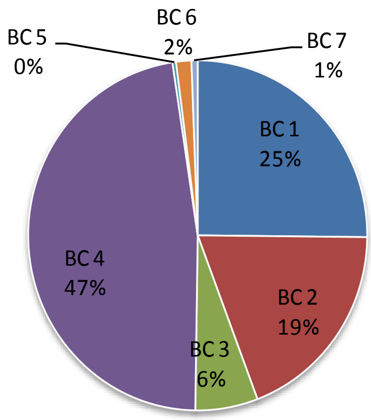
Environmental Impact	*BC1 Distribution*	*BC2 Industry oil*	*BC3 Industry dry*	*BC4 Power*	*BC5 DER oil*	*BC6 DER dry*	*BC7 Separation /isolation*
Total Energy (GER) *[PJ]*	201.35	152.91	47.72	379.24	2.71	11.66	4.73
of which electricity *[TWh]*	17.95	13.80	4.36	33.77	0.24	1.01	0.38
Water process *[mln m^3]*	12.85	9.81	3.06	24.06	0.17	0.71	0.27
Waste,non-hazardous/landfill *[kton]*	848.52	588.87	110.14	1774.00	13.09	36.27	64.55
Waste, hazardous/ incinerated *[kton]*	41.90	24.67	2.38	89.94	0.53	0.65	0.09
Emissions to air							
Greenhouse Gases in GWP100 *[Mt CO_2 eq.]*	8.83	6.70	2.10	16.61	0.12	0.52	0.21
Acidification, emissions *[kt SO_2 eq.]*	56.66	43.05	12.44	110.32	0.78	2.96	1.88
Volatile Organic Compounds (VOC) *[kt]*	0.14	0.09	0.02	0.28	0.00	0.01	0.00
Persistent Organic Pollutants (POP) *[g i-Teq.]*	3.62	2.36	0.74	6.22	0.05	0.32	0.14
Heavy Metals *[ton Ni eq.]*	5.79	4.07	0.95	11.50	0.08	0.25	0.26
PAHs *[ton Ni eq.]*	1.44	0.98	0.38	2.69	0.03	0.21	0.04
Particulate Matter (PM, dust) *[kt]*	6.09	3.55	0.63	11.88	0.07	0.24	0.39
Emissions to water							
Heavy Metals *[ton Hg/20]*	2.21	1.43	0.47	3.72	0.04	0.17	0.06
Eutrophication *[kt PO_4]*	0.05	0.03	0.01	0.08	0.00	0.00	0.00

Table 4-29: Environmental impacts of the EU-27 stock in 2005 for all base-cases

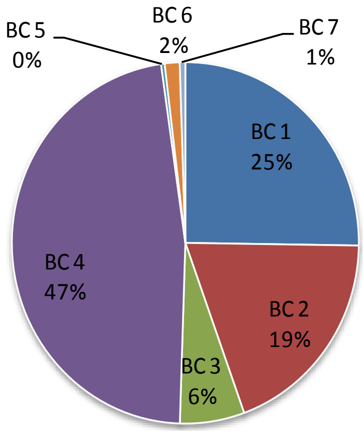
Summary of environmental impacts of base-cases as a percentage of total impact are presented in Figure 4-9. As the figure shows, power transformers have the greatest impacts within the sector and represent less than 2% of the total stock. The share of power transformers remains relatively constant, between 47% (for total energy, water for processing, GWP, PAHs) and 56% for hazardous waste. Distribution transformers, representing around 61% of the stock only account for 25% of impacts on average, with 26% contribution for hazardous waste (because of mineral oil thermal recycling) and VOC emissions. Industry oil-immersed transformers finally represent between 15%

(hazardous waste) and 19% (total energy, GWP, acidification) of the environmental impacts for a similar share of the stock (14%). DER dry-type transformers have a particularly high share in terms of PAHs (4%) despite a low number of such transformers in operation, because of their high aluminium content. Finally, although they represent 20% of the stock, the separation and isolation transformers account for a negligible share for all impacts, partly because of the low availability factor applied to this base-case and the shorter lifetime considered.

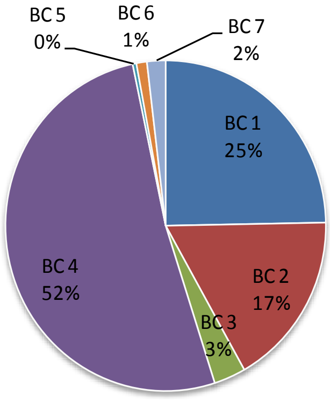
Total Energy (GER)



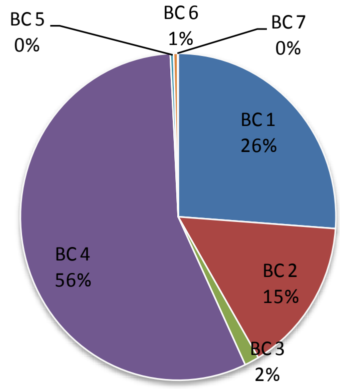
Water process



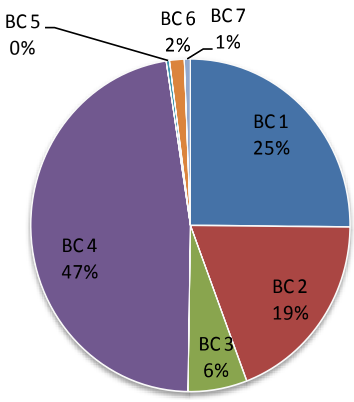
Waste,non-hazardous/landfill



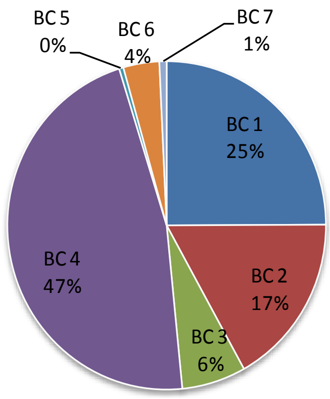
Waste, hazardous/ incinerated



Greenhouse Gases in GWP100



PAHs



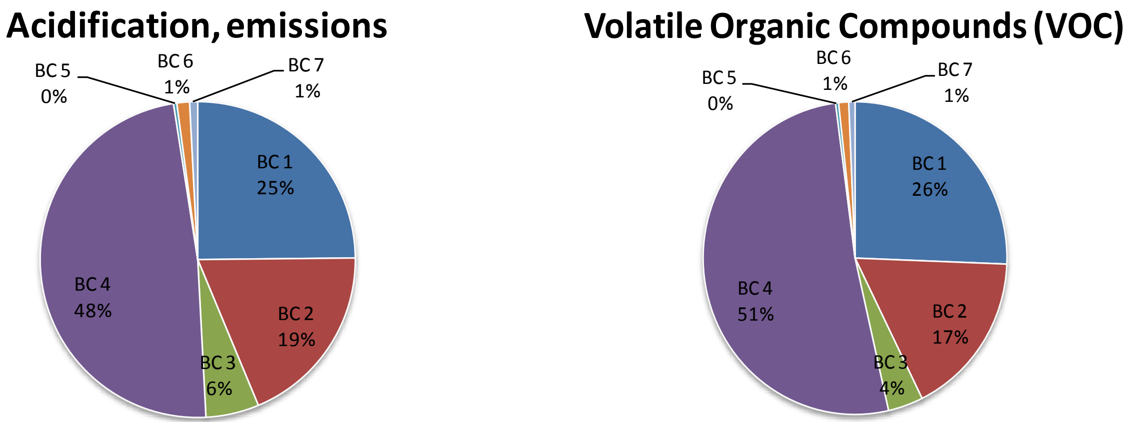


Figure 4-9: Base-cases' share of the environmental impacts of the 2005 stock

Figure 4-10 focuses on the shares of the electricity consumption. They are similar to other impacts as power transformers represent 47% of the total electricity consumption of the transformers stock while distribution transformers account for 25% of the total and oil-immersed industry transformers for 19%. The total electricity consumption of power and distribution transformers is about 71.5 TWh which represents about 2.1% of the EU-27 total electricity generation[103].

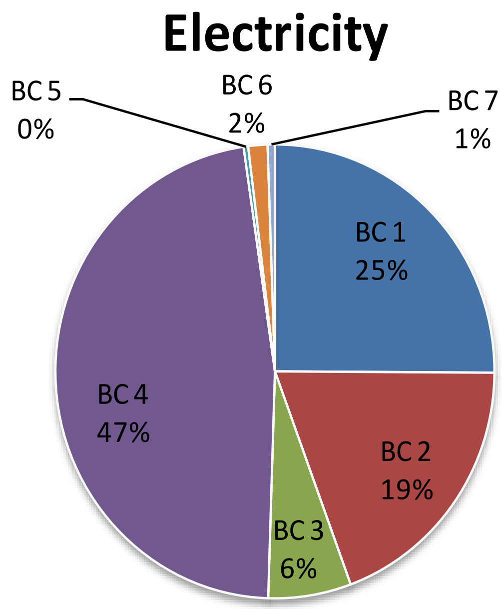


Figure 4-10: Base-cases' share of the electricity consumption of the 2005 stock

[103] Source Eurostat: EU27 gross electricity generation in 2007 = 3 362 TWh; EU27 electricity consumption in 2007 = 244 million toe = 2 837 TWh.

Regarding studies to be considered in this task for results comparison and input/output analysis (IOA), the EIPRO[104] results are relevant as the authors performed a review of and comparison with other available IOAs (Moll et al. 2004, Nijdam and Wilting 2003, Kok et al. 2003, Weidema et al. 2005).

The methodology developed in the EIPRO study is a top-down oriented approach based on environmental input/output analysis E-IOA (where the analysis of emissions is based on quantification of economic activities in monetary terms) whereas the MEEuP, which will be used here[105], is a bottom-up approach (which extrapolates market-oriented LCAs to arrive at the environmental interventions associated to a product group). It is thus interesting to compare our results with the EIPRO results. The category under the scope of EIPRO is "Power, distribution and specialty transformers" so that it includes some smaller transformers not taken into account in this study (other than separation/isolation transformers). Only three environmental impacts are presented in the study in a similar manner: GWP, acidification and eutrophication. The other impacts such as Human toxicity and Ecotoxicity are regrouping different emissions that are separated in EcoReport (VOC, POP, PAHs...). The results in Table 4-30 show the EIPRO outcomes, which are the impacts caused by the products consumed in the EU-25 per year. The values have been calculated by using the annual consumer expenditure given in Table 4-31 (3 942 mln €) because impacts in EIPRO are given for one euro spent by type of product but no market data is provided for transformers. Also these impacts only refer to the cradle-to-gate phases as transformers are considered as intermediate products: thus the use phase and end-of-life are not taken into account. The EcoReport outcomes refer to the impacts of the distribution and power transformers sold in 2005, taking into account the production and distribution phases only.

Impact	***Fraction of the total impacts in EU-25, for 1€***	***EIPRO outcome (cradle to gate)***	***EcoReport outcome (production and distribution impacts only)***
GWP	3.34E-13	6.20 Mt CO_2 eq	2.43 Mt CO_2 eq
Acidification	3.89E-13	66.1 kt SO_2 eq	35.6 kt SO_2 eq
Eutrophication	3.84E-13	15.9 kt PO_4 eq	0.102 kt PO_4 eq

Table 4-30: Comparison of EIPRO and EcoReport results

Given the differences in the methodology of the two studies, the comparison of the results is not straightforward. Besides, the EIPRO results are based on data referring to the 1990s in the US, while the consumer expenditure used to scale the EIPRO impacts refers to 2005.
For GWP and acidification potential, the EcoReport (taking into account only the production and distribution phases impacts) gives smaller values than EIPRO, but in the

[104] The objective of the EIPRO (Environmental Impact of PROducts) study, started in 2004, was to identify products with the greatest environmental impact from a life cycle perspective for EU-25. This study constituted the first phase of a bigger project whose second phase aimed to identify products with the greatest potential for environmental improvement. This project was led by the Institute for Prospective Technological Studies (IPTS) in Seville, which is part of the DG Joint Research Centre. BIO was invited to participate to the expert group which followed the entire study.

[105] This is also a similar method that BIO developed in 2002-03 for the EC-DG ENV in the framework of the study entitled 'Study on external environmental effects related to the life cycle of products and services'. As the pioneer work in that field, it was amongst those reviewed in the scope of the EIPRO study.

same order of magnitude. The difference might be partly due to the inclusion of specialty transformers in the scope of EIPRO.
About the eutrophication impact, it is around 150 times smaller than the EIPRO outcome. The different approaches (top-down and bottom-up) of each study and the assumption made in both methodologies may explain the important gap for this single impact, even if the same weighting factors for the contribution of compounds (these suggested by CML methodology) were applied in both studies.

4.5.3 Total annual expenditure in 2005

Regarding the total consumer expenditure in 2005 related to the seven base-cases, about 72% of the total costs are due to electricity losses. The distribution per base-case is given in Figure 4-11 and details on consumer expenditure are presented in Table 4-31.

	BC1 Distribution	***BC2 Industry oil***	***BC3 Industry dry***	***BC4 Power***	***BC5 DER oil***	***BC6 DER dry***	***BC7 Separation /isolation***	***TOTAL***
EU-27 sales *[units]*	140 400	43 200	8 047	3 046	580	2 320	75 000	272 593
Share of the EU-27 sales	51.5%	15.8%	3.0%	1.1%	0.2%	0.9%	27.5%	100%
Product Price *[mln €]*	860	472	131	2 302	11	65	101	3 942
Electricity *[mln €]*	1 385	1 068	338	2 606	71	300	30	5 798
Total *[mln €]*	2 244	1 540	470	4 909	81	365	131	9 740

Table 4-31: Total Annual Consumer expenditure in EU-27 in 2005

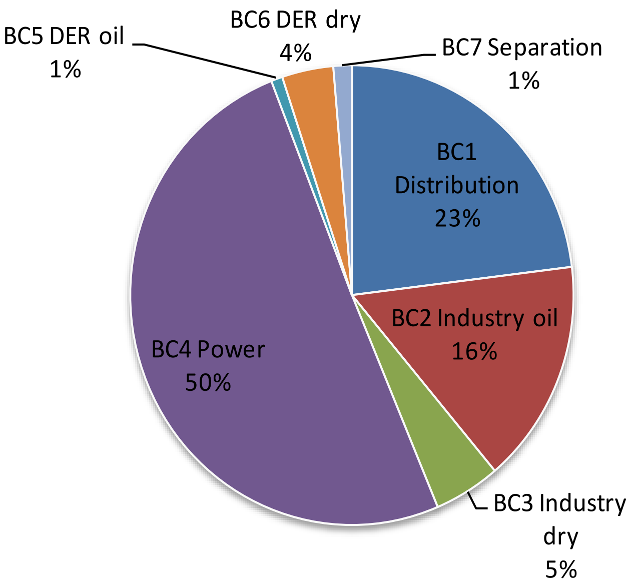


Figure 4-11: Base-cases' share of the total consumer expenditure in 2005

The contributions to the total consumer expenditure are very similar to the ones to the environmental impacts. Total consumer expenditure in 2005 related to power transformers represents 50% of the total. Distribution transformers are the next highest with 23% and third come industry oil-immersed transformers accounting for 16% of the total consumer expenditure. The four remaining base-cases only represent 11% altogether. Total consumer expenditure includes product and electricity costs over the product lifetime but does not take into account money received for materials at disposal.

4.6 Conclusions

The environmental impacts assessment carried out with the EcoReport tool for each base-case show that the use phase is by far the most impacting stage of the life cycle in terms of energy consumption, water consumption, greenhouse gases emissions and acidification. The production phase has a significant contribution to the following impacts: generation of non-hazardous waste, VOC, POP, PAHS emissions and eutrophication. Finally the end-of-life phase is significant for the generation of hazardous waste, the particulate matter emissions and the eutrophication, either because of mineral oil or resin. Therefore, the analysis of the improvement potential in chapter 6 will focus on technologies that reduce the electricity losses, and also on alternative material (e.g. oil) reducing environmental impacts.

Despite a small amount of power transformers in stock, these transformers are responsible for about half of the overall impacts due to power and distribution transformers in EU. They also represent about half of the annual consumer expenditure as they are much more expensive than the distribution transformers. DER transformers still represent a very small share of the overall environmental impacts but it is expected to grow in the near future because of the rising stock of this type of transformer.

Chapter 5 will examine the improvement options of transformers considered as best available technologies, in an attempt to improve upon the base-cases.

CHAPTER 5 TECHNICAL ANALYSIS BAT AND BNAT

Scope:
This section presents a description and technical analysis of the Best Available Technology (BAT) and Best Not yet Available Technology (BNAT) that can be implemented for products defined in chapter 1.
BAT is defined as:
- "Best" shall mean most effective in achieving a high level of environmental performance of the product;
- "Available" technology shall mean that developed on a scale which allows implementation for the relevant product, under economically and technically viable conditions (expected to be introduced at product level within at least 2-3 years), taking into consideration the costs and benefits, whether or not the technology is used or produced inside the Member States in question or the EU-27, as long as they are reasonably accessible to the product manufacturer.
BNAT is defined as:
- "Best" and "Available" as defined before;
- "Not yet" available technology shall mean that not developed yet on a scale which allows implementation for the relevant product but that is subject to research and development.
This section partly provides the input for the identification of part of the improvement potential (task 6), i.e. especially the part that relates to the best available technology.
Both for BAT and BNAT barriers for take-up are assessed, such as cost factors or availability outside Europe or research and development outside Europe.
This chapter deals with technological improvement options for distribution and power transformers as defined in in the scope for this study in chapter 1. Technological improvement options for the smaller industrial transformer are identical to those of lot 7 on external power supplies. They are not described hereafter anymore. The main difference is that there is a strong impact of insulation and cooling on transformer design in distribution and power transformers while this is not the case for the smaller transformers that operate on the mains voltage only(230/400 VAC). Moreover the improvement options are also very different, e.g.: smaller transformers can often be replaced by an electronic power supply if no 50 Hz sine wave is needed (halogen lamps, DC power,..), most transformers are single phase, circular wires are used, compactness is an important issue, ...

Summary:
In this chapter several improvement options are identified compared to the base case (chapter 4).
This task examines the improvement options of transformers considered as Best Available Technologies, in an attempt to improve upon the base-cases. It explains that transformers can be improved by using similar technology based on silicon steel transformers with the following options:

- The use of copper compared to aluminium conductors;
- The use of a circular limb core cross-section;

Also, other potential improvements include:

- The use of High permeability Grain Oriented Electrical Steel (HGO) with lower losses (Cold rolled Grain-Oriented steel, High permeability steel, Domain Refined high permeability steel);
- The use of amorphous steel (significant lower core losses) (not possible to larger power transformers);
- The use of transformers with silicon liquid, synthetic esters or biodegradable natural esters instead of dry cast resign transformers or mineral oil;
- Increasing the cross section of the conductor and cross section of the core;
- Core construction techniques (e.g. mitred lapped joints);
- The transformer design variability combining above improvements;
- Improved coatings between the laminations of conventional silicon steel;
- Reducing the transformer noise.

All improvement options increase the product price. Several improvement options increase the product volume and mass.

The improvements options considered as Best Non Available Technologies concern:

- Further improvements of Grain oriented magnetic steels, amorphous microcrystalline material as core materials;
- The use of superconducting technology;
- The use of smart grid technology to switch off an by-pass transformers off peak load (system level);

5.1 Best Available Technologies – BAT

5.1.1 BAT assumed to be part of common practice and the base case products

Several well-established manufacturing technologies are already included in the base case types defined in chapter 4. They are described in the next sections. As opposed to the later section (5.1.2), the improvement potential of these technologies is not quantified because it is was assumed to be included in the defined base cases in chapter 4. Hence these technologies are assumed common practice technologies that are nevertheless BAT and as a consequence there are also no barriers for take-up.

5.1.1.1 Use of stranded rectangular wires or conductor foils

In order to achieve a good space-factor cross section, rectangular wires or foils are used to construct the transformer coils[106]. They achieve the best 'copper filling' and reduce therefore conduction losses compared to circular wires (Figure 5-1). Wires of circular cross-section cannot be wound into windings having as good space-factor as rectangular-section wire, nor does it produce a winding with as high a mechanically stability. It is also a common practice to use stranded insulated wires to avoid eddy-current losses (see chapter 1) in power and distribution transformers[107](Figure 5-1). . Rectangular wires and foils have the best 'copper filling' per unit area in the core window, particularly when compared to round wire – however, some manufacturers have used "flattened" or "smashed" wire, which involves pulling a spool of round wire through two roller-compressors while winding the transformer on a lathe. This creates a wire that is flat on the top and bottom and round on the sides, and results in a better space factor than round wire (although still not as good as rectangular wire or foil).

[106] M.J. Heathcote (2007):'J&P Transformer Book', p. 60, ISBN 978-0-7506-8164-3
[107] M.J. Heathcote (2007): 'J&P Transformer Book', p. 55, ISBN 978-0-7506-8164-3

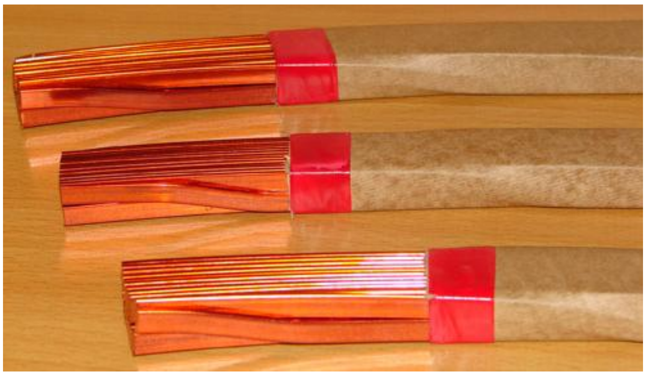


Figure 5-1: Stranded rectangular copper wires

5.1.1.2 Use of stacked cores with laminated steel and improved coatings

All base case transformers (chapter 4) use stacked cores with laminated steel (Figure 5-2). The improvement options from different steel grades or using amorphous steel will be discussed in later sections.

The main reason for this practice is to reduce core losses that are composed of[108]:

Hysteresis loss Wh[W/kg] $\sim f \times Bmax^{n}$ (equation 5.1)

Eddy current loss We[W/kg] $\sim \rho \times t^{2} \times f^{2} \times Bmax^{2}$ (equation 5.2)

Where,

n is the Steinmetz exponent that varies typically between 1.6 and 2
f is the frequency [Hz] that is typically 50 Hz
t is the thickness of the material
ρ is the resistivity of the material
Bmax is the maximum flux density [T]

Figure 5-2: Transformer with boltless clamped core of stacked laminated silicon steel

It is also assumed that all manufacturers use proper techniques to maintain the insulation between the laminated plates. Cutting of laminates inevitably produces edge burrs that could create undesired contacts between plates[109], which are avoided by a

[108] M.J. Heathcote (2007): 'J&P Transformer Book', p. 42, ISBN 978-0-7506-8164-3
[109] M.J. Heathcote (2007): 'J&P Transformer Book', p. 109, ISBN 978-0-7506-8164-3

burr grinding process completed with additional insulation. Also modern cutting tools can reduce this to a very minimum edge burr (laser, water jet, ...). At the edges also overlaps can be used.
Most electrical steels are supplied with glass-type insulation coatings. Certain manufacturers have developed new coating technologies which can enhance the efficiency and performance of the electrical steels. AK Steel, for example, has introduced Carlite 3 insulation which provides a beneficial tensile stress that contributes to better magnetic properties and decreased stress sensitivity of the material[110]. These improvements are also included in the grouped improvement options, see section 5.1.2.8, and are applied in base case products today.

5.1.1.3 Avoid that the flux to deviate from the grain direction in grain oriented silicon steel

A potential disadvantage of grain-oriented core steels is that any factor which requires the flux to deviate from the grain direction will increase the core loss[111], which becomes increasingly important in the case of so called HGO core steel (see 5.1.2.3). Such factors include any holes through the core. Common engineering techniques to avoid this are: boltless clamped core constructions (Figure 5-2), increasing the core cross-section at those points to reduce the flux and mitred cut step-lapped core joints instead of square core joints (Figure 5-3). The relationship between the core loss and fully assembled core is also known as the building factor and is generally about 1.15.
In smaller industrial transformers (e.g. isolation/separation/control < 63 kVA) it is not used because it is not economical for such a small construction.

Figure 5-3: Mitred cut step-lapped core joints

5.1.1.4 Magnetic flux reduction in the core yokes compared to limbs

It is also common to increase the core cross sectional area in the core yokes compared to the core limbs. This flux reduction reduces above proportional the losses, i.e. more then linear(see 5.1.1.2). So-called *core limbs* are the part of the core within the transformer coils And *core yokes* are the part of the core connecting between the limbs. Another common engineering practice is using step-lapped joints[112], which facilitates the boltless clamped core yoke construction (Figure 5-2).

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[110] see p.4 of the following PDF: http://www.aksteel.com/pdf/markets_products/electrical/Oriented_Bulletin.pdf)
[111] M.J. Heathcote (2007): 'J&P Transformer Book', p. 111, ISBN 978-0-7506-8164-3
[112] M.J. Heathcote (2007): 'J&P Transformer Book', p. 115, ISBN 978-0-7506-8164-3

5.1.1.5 Avoiding stress in silicon steel cores

Mechanical stress contributes to increased core losses and should be avoided[113]. Therefore annealing is applied to restore its initial core loss properties. Common power and distribution transformer constructions avoid these stresses. This stress-relief annealing could be a requirement only for constructions using bended silicon steel, e.g. C-cores (Figure 5-4). The most efficient steel grade does not allow this annealing (domain refined silicon steel, see 5.1.2.3).

Figure 5-4: Single phase transformer with a bended laminated silicon steel C-core

5.1.2 BAT with identified barriers for take-up

As opposed to the previous section (5.1.3), the technologies described hereafter are not fully adopted in the base case products identified in chapter 4. The barriers for take-up are therefore identified and input for the quantification of improvement options (chapter 6) is provided.

5.1.2.1 Use of copper compared to aluminium conductors

Winding losses occur in both the primary and secondary windings when a transformer is under load. These losses, the result of electrical resistance in both windings, vary with the square of the load applied to the transformer. Both aluminium and copper are used in current distribution transformer designs and are available for use in standard wire sizes and foils. It is common to have copper in the high-voltage (HV) windings. According to the technology of the manufacturer and the level of the aluminium or copper losses is used in the low-voltage (LV) windings. In these LV windings, aluminium can be used in the form of flat, rolled foils to reduce eddy current losses. Transformers typically use Electrolytic Tough Pitch Copper (Cu-ETP), which is a high-conductivity copper (standard ISO/R1337). Aluminium alloy 1350-H111 temper (ANSI standard) exhibits the highest electrical conductivity and is most often used in transformers. The most important technical parameters for comparison are included in Table 5-1. All manufacturers have the knowledge of the technologies to choose the most appropriate and cost effective raw material for conductor (aluminium or copper) according to the level of losses and commonly achieved that[114]. See CIRED n°108 of 2008

[113] M.J. Heathcote (2007): 'J&P Transformer Book', p. 109, ISBN 978-0-7506-8164-3
[114] CIRED (2008) Sacotte, M. Faltermeier, J.-F. Folliot, P. Sacre, A, 'Benefits of using high efficiency power equipment that reduce distribution system losses', Franfurt, paper 108

The most efficient transformers per volume are copper wound transformers. By utilizing aluminium conductor material at a lower current density (i.e., larger conductor cross-sectional area (CSA)), aluminium transformer windings can be built with essentially the same load losses as copper. However, aluminium conductors increase core losses due to their larger core frames, necessitated by the larger winding space ("core window") through which the windings must pass. When the transformer volume does not matter for a defined set of load and no load losses both an aluminium and a copper coil transformer can be designed in most cases (see section 5.1.2.8). In dry-type transformers, aluminium has an technical advantage related to overloading because the coefficient of expansion of aluminium is the same as cast resign.

Property	Aluminium	Copper
Electrical Resistivity (relative)	0.61	1
Thermal Conductivity(Cal/s.cm.K)	0.57	0.94
Relative weight for the same conductivity	0.54	1
Cross section for the same conductivity	1.56	1
Tensile Strength kg/cm²	844	2250
Spefific weight (kg/dm³)	2.7	8.9
Electrical Resistivity (mOhm.mm) (20°C)	26.5	16.7
Thermal coefficient of resistance (1e-6/K)	3770	3900

Table 5-1: Characteristic differences between Copper and Aluminium

The effect of substitution of Aluminium by Copper in the same design and volume on mass can approximately be quantified by:

$$Mcu-new \ = MCu + MAlu \times \rho Cu/\rho Alu \qquad \text{(Equation 5.3)}$$

Where,

MCu-new is the copper weight in the new design
MCu is the copper weight in the old design
MAlu is the aluminium weight in the old design
ρCu is the specific weight of copper
ρAlu is the specific weight of aluminium

The effect of substitution of aluminium by copper in the same design and volume on load loss (Pk) can approximately be quantified by:

$$Pknew = \frac{(\frac{MCu}{\rho Cu}+(\frac{MAlu}{\rho Alu})\times 0.61)\times Pk}{(\frac{MCu}{\rho Cu}+\frac{MAlu}{\rho Alu})} \qquad \text{(Equation 5.4)}$$

Where,

Pknew is approximately the load loss in the new design
Pk is the load loss in the old design with aluminium

Formula 5.3 and 5.4 should be used very carefully and are relevant only for the same technology.

Summary of achieved benefits in included in section 5.1.2.8 with grouped improvement options.

Potential barriers for up-take
The higher material price of copper can be a barrier (see chapter 2 for data).
Aluminum wound transformers are lighter in weight than copper wound equivalents.

An assessment of these improvement options related to BOM and cost compared to the base case (chapter 4) can be done with previous formulas but will also be included in section 5.1.2.8. This section will group several improvement options due to the many engineering trade-offs possible.

5.1.2.2 Use of a circular or cruciform limb core cross-section

Core laminations are built up to form a limb or leg having as near as possible circular cross-section[115] in order to obtain optimum use of space within the windings and reduce load losses (Pk) (Figure 5-2). The stepped cross-section approximates to a circular or so-called cruciform shape depends only on how many widths of strip a manufacturer is prepared to cut and build.
In smaller industrial transformers (e.g. isolation/separation/control < 63 kVA) rectangular or other core cross-sections are used because it is not considered economical for such a small construction to assemble stepped core cross-sections.

[115] M.J. Heathcote (2007): 'J&P Transformer Book', p. 107, ISBN 978-0-7506-8164-3

Shape limb core cross-section	filling
perfect circular	1
7-step circular	0.93
11-step circular	0.95
1-step or rectangular	0.64

Table 5-2: Core Filling for different shapes limb core cross sections

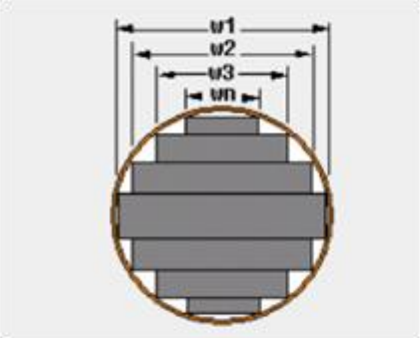

Figure 5-5: -step limb core cross-section[116]

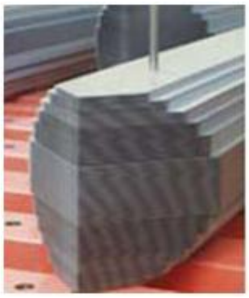

Figure 5-6 step limb cross-section

Most often 7-step (Figure 5-5 and Figure 5-6) or 11 step designs are used, the difference in filling factor is minimal (see Table 5-2).
Amorphous metal (see 5.1.2.4) transformers have only rectangular core form cross-sections available.
Also hexagonal core form transformers (see 5.1.3.3) might have difficulties to achieve a perfect circular limb core cross-section.
In practice the sections have a so-called 'cruciform that leads to the best overall design results. There is a machine manufactured by a Germany company called "Georg" which completely automates the processing of core steel from a coil into a stacked, circular (or oval), mitred corner core. These are expensive machines and are used by all the major transformer manufacturers. The Georg machine is very precise, managing all the

[116] Technical support document: Energy efficiency program for commercial and industrial equipment: electrical distribution transformers', U.S. Department of Energy (DOE), September 2007, chapter 5

different dimensions - widths, lengths, and angles – which it then stacks to build cores that look like this:

Potential barriers for up-take
The price to cut and handle many widths of strips might be a barrier for silicon steel transformers. However, the "price to cut and handle" the different widths should not be seen as a barrier because this is actually a highly-automated process for manufacturers across Europe.
Rectangular core or hexagonal core form transformers are limited to reduce load losses by their core cross-section shape. However as long as the limits are realistic, load losses in these designs can also be reduced by utilizing conductor material at a lower current density (i.e., larger conductor cross-sectional area).
This element is taken into account when discussing amorphous transformers in section 5.1.2.4).
An assessment of these improvement options related to BOM and cost compared to the base case (chapter 4) will be included in section 5.1.2.8. This section will group several improvement options due to the many engineering trade-offs possible.

5.1.2.3 Use of grain oriented silicon steel with lower losses

The application of better grades of grain oriented steel and decreasing of lamination thickness can lead to a reduction of losses. The first production patents on grain-oriented electrical steels were issued in 1933. Figure 5-1 describes the timeline of grain oriented silicon steel development. The main developments[117] are described hereafter.

Cold rolled Grain-Oriented Steel (CGO)
Oriented electrical steels are iron-silicon alloys that were developed to provide the low core loss and high permeability required for more efficient and economical electrical transformers. These magnetic materials exhibit their superior magnetic properties in the rolling direction. This directionality occurs because the steels are specially processed to create a very high proportion of grains within the steel which have similarly oriented atomic crystalline structures relative to the rolling direction.

High-permeability steel (HGO)
Later improvements were obtained by introducing around 0.025 per cent of aluminium and eliminating one of the cold-rolling stages in the production process. At high flux densities of 1.7 T its permeability was 3 times higher because of the improved orientation and the presence of a high tensile stress introduced by the so-called stress coating. This stress helps reducing eddy current losses, however there is also a reduction in hysteresis loss. Later on other alloys based on MnSe plus Sb and Bwere introduced. In addition, these "super-oriented" materials provide the potential for producing less noisy core structures due to lower magnetostriction.

Domain Refined High-permeability steel (HGO-DR)
Further improvements introduced in the early 1980s are based on forcing the existing domains to subdivide, the refined domain wall spacing requires less movement during AC magnetization, thereby reducing core loss in the steel.
This is most often done by laser irradiation. Stress-relief annealing will nullify the beneficial effects of laser scribing domain refinement. These materials are most appropriate for stacked-core applications where stress-relief annealing is not needed. ,
There is also mechanically-scribed Domain refined (HGO-DRM) electrical steel available often referred as "Unicore", developed in Australia. Here domain refined material can

[117] [117] M.J. Heathcote (2007): 'J&P Transformer Book', p. 45, ISBN 978-0-7506-8164-3

be used without annealing. The Unicore technique is today accepted in more than 30 countries and is also being tested in the EU.

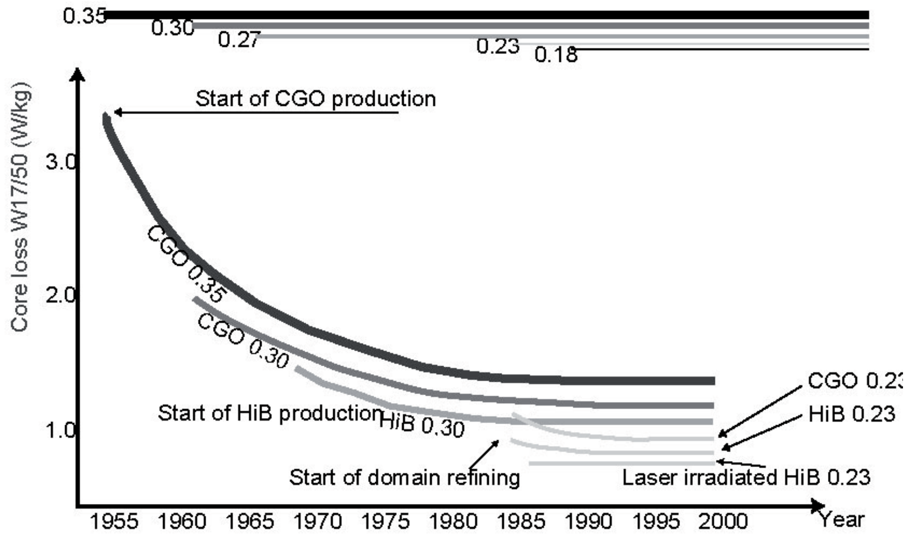

Figure 5-7: Core loss evolution 1955-2000: Production technology and possible thickness (Targosz et al. 2008[118])

Grading and designation of grain-oriented steels
For uniformity in specifying, producing, and purchasing, electrical steels are primarily graded by core loss.
In the EU the most used grading system is according to EN 10107, which is equivalent to IEC 60404-8-7. The first number stands for core loss at 1.7 T and the second for steel thickness (Table 5-2). Another frequently used system in Business is that of the American Iron and Steel Institute (AISI), in which each grade is assigned a type number according to its core loss. The M stands for magnetic material.

[118] Targosz, Roman; Topalis, Frangiskos; et al.; Analysis of Existing Situation of Energy-Efficient Transformers – Technical and Non-Technical Solutions, Report (Final Version of Deliverable No.1) from the EU-IEE Project "Strategies for Development and Diffusion of Energy-Efficient Distribution Transformers – SEEDT", Project No. EIE/05/056/ SI2.419632., 2008

Type acronym	AISI	EN 10107	Thickness	Max. specific loss (W/kg)			Typical specific loss (W/kg)			
			(mm)	50 Hz		60 Hz	50 Hz		60 Hz	
				1.5T	1.7T	1.7T	1.5T	1.7T	1.5T	1.7T
CGO	M2		0.18	0.68	-	0.89	-	-	-	-
CGO	M3	M120-23S	0.23	0.77	1.20	1.58	0.73	1.15	0.96	1.51
CGO	M4	M130-27S	0.27	0.85	1.30	1.71	0.83	1.24	1.09	1.63
CGO	M5	M140-30S	0.3	0.92	1.40	1.84	0.87	1.26	1.15	1.66
CGO	M6	M150-35S	0.35	1.05	1.50	1.97	0.99	1.42	1.30	1.87
HGO-DR		M090-23P*	0.23	0.65	0.90	1.18		0.86		1.13
HGO		M100-23P	0.23		1.00	1.32		0.96		1.27
HGO-DR		M095-27P*	0.27	0.71	0.95	1.25		0.92		1.21
HGO		M103-27P	0.27		1.03	1.36		0.97		1.28
HGO-DR		M100-30P*	0.30		1.00	1.32		0.97		1.28
HGO		M105-30P	0.30		1.05	1.38		1.02		1.34
HGO-DR		-	0.30		1.00	1.32		0.97		1.28
HGO-DRM		-	0.30		0.92					
HGO-DRM		-	0.23		0.85					

Table 5-3: Designation and specific losses of different silicon steel grades (price info see chapter 2).

Potential barriers for up-take
The M2 material is only available from one manufacturer (outside Europe) and its application at 1.7 T magnetic induction is is not specified in the EU. Remark: M2-material (= CGO 0,18mm) is mainly used in the US-Market (for single phase pole transformers), but rarely in the EU.
HGO-DR material cannot be applied when annealing is required unless Unicore-technique is applied. This might be a barrier for bended core forms that require stress-relief annealing, e.g. in hexagonal core form transformers (see section 5.1.3.3).

An assessment of these improvement options related to BOM and cost compared to the base case (chapter 4) can be deducted from material properties but will also be included in section 5.1.2.8. This section will group several improvement options due to the many engineering trade-offs possible.

5.1.2.4 Use of Amorphous Metal

Description of technology and its improvement:
Over the last 30 years, so-called amorphous metal or glassy metal with magnetic properties has been proposed and used as transformer core metal. Unlike ordinary alloys, amorphous alloys do not have a crystal structure. They rely for their structure on a very rapid cooling rate of the molten alloy and the presence of a glass-forming element such as boron. Typically they might contain 80% iron with the remaining boron and silicon. They are different from conventional crystalline alloys in their magnetic properties and in their mechanical properties (such as hardness and strength). Core losses are significantly reduced and they are easy to magnetize, however due to the reduced amount of iron the saturation flux is also lower. The typical chemical composition may be found in the Metglas® Material Safety Data Sheet of their 2605 SA1 Iron Based Alloy.

B is the magnetic induction in Tesla and H the magnetic field in Ampere per meter. The most representative points such as magnetic induction at 80 A/m(B(80 A/m)), the remanence magnetic induction (Br) and the coercivity magnetic field (Hc) are listed in Table 5-4.

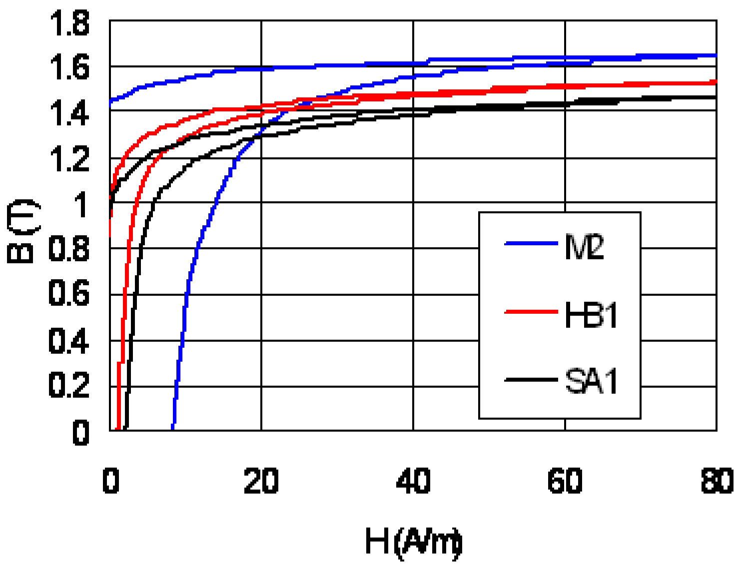

Figure 5-8: BH Curve for M2-Grade Silicon Steel, Conventional 2605SA1 and New 2605HB1 Amorphous Metal(Source: Hitachi METGLAS)

Material	B(80 A/m) (T)	B_r (T)	H_c (A/m)
M2	1.64	1.35	8.2
SA1	1.46	0.95	2.2
HB1	1.53	0.90	1.2

Table 5-4 Basic magnetic properties of for M2-Grade Silicon Steel, Conventional 2605SA1 and New 2605HB1 Amorphous Metal (Source: Hitachi METGLAS)

The main improvement is significant lower core losses compared to silicon steel (Table 5-5).
The core losses of material 2605SA1 are proportional to frequency and maximum flux density:

$$Pcore\left[\frac{W}{kg}\right] \sim f^{1.51} \times Bmax^{1.74} \qquad \text{(equation 5.5)}$$

Where,

f is the frequency [kHz] that is typically 0.05 kHz
Bmax is the maximum flux density [T]

Type acronym	Thickness	Finished Core Test Values at 25°C(about twice single strip values)-50 Hz (W/kg)									Saturation Induction
	(mm)	50 Hz								60 Hz	T
		1,3T	1,35T	1,4T	1,45T	1,5T	1,55T	1,6T	1.7T	1,35T	
SA1	0.025	0.21	0.23	0.25	0.27	0.3	0.28	NA	NA	0.29	1.56
HB1	0.025	0.21	0.22	0.24	0.27	0.29	0.25	0.34	NA	0.26	1.64
HGO-DR	0.23					0.65			0.81		2

Table 5-5: Maximum specific losses for amorphous steel

The global market activities and production capacity are described in the related section in chapter 2.

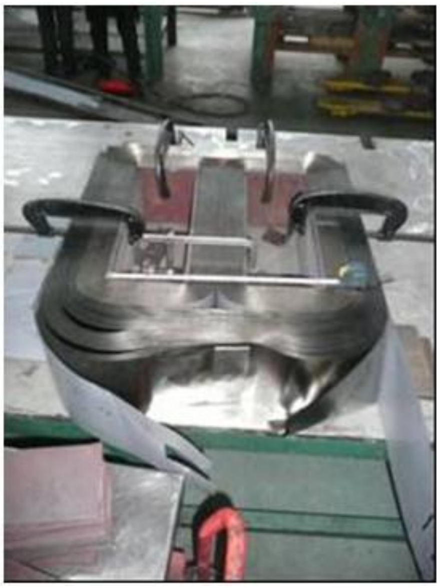

Figure 5-9: Amorphous metal transformer core under construction[119]

[119] Picture from Hitachi

Figure 5-10 Stacked silicon steel core under construction

***Main technical differences of amorphous core transformers compared to silicon steel*:**

- Amorphous metal cores have a lower saturation magnetic flux density than the silicon steel transformer cores. Lower flux density in amorphous metal cores means that to achieve similar levels of total core flux, as in normal transformers, the amorphous core must have a larger cross-section. A larger core cross-section means more winding conductor length, with an increase in resistance and hence an increase in the load losses (Pk). A design induction of 1.35T allows 110% overvoltage without saturation. At 85C core temperature (hotter than cores get in normal operation), 110% overvoltage is 7 VA/kg.
- The AMT core space factor should be 84%. The AMT core material density is 7,200 kg/m3. The cores should be supported from the coils. ;
- Because of the rather specialized process needed to manufacture the amorphous metal (an extremely rapid cooling of molten metal is required) it can only be produced in very thin and long strips. The material is relatively brittle and cannot easily be cut to shape. During the process, due to the brittleness, there are some risks of particles inside the active part of the transformers that could lead to dielectric breakdown. Amorphous ribbon is typically available in widths of 142, 170 and 213.3 mm, multiple widths can be stacked side by side;
- It requires 'Wound core' technology and therefore relies on the use of only one strip width. This results in a rectangular cross section of the core (Figure 5 8). This rectangular core cross-section means more winding conductor loss (see also section 5.1.2.2);
- Another difference between oval shaped and rectangular coils are the forces during short circuit testing. However the unbalanced axial forces are nearly eliminated by using a sheet or foil wound low voltage coil. Use of sheet wound LV coils is an almost universal technique (see section 5.1.1.1). The low voltage coil then balances its current distribution to match the high voltage coil current distribution eliminating most of the axial force. This might also explain why until now no power transformers were developed based on amorphous material. With proper engineering transformers can pass the short circuit qualification tests of European Utilities[120].;

[120] B. JARRY (2009), P. LAUZEVIS P. LAGACHE M. SACOTTE, 'AMORPHOUS SHEET CORE TRANSFORMERS UNDER EXPERIMENTATION ON THE ERDF NETWORK', CIRED conference paper, 20th International Conference on Electricity Distribution Prague, 8-11 June 2009.

- Both 3-phase 3-limb and 3-phase 5-limb core forms can be constructed. See section 5.1.3.3 for technical differences;
- Due to their bigger size and construction as well as to the higher magnetostriction value of AM compared to GO these transformers tend to have higher noise levels when constructed without additional sound level reducing measures. According to T&D Europe, European manufacturers have the feeling that the difference of noise is probably around 10db (A) between amorphous transformers and the better level of losses with standard magnetic steels transformers (400KVA);
- The magnetization requirement of these transformers is generally lower compared to silicon[121] due to the higher magnetic permeability, at least if one stays away from magnetic saturation. AMT requires typically 0.5 VA/kg (1.3 T) while silicon 0.7 VA/kg;
- The higher magnetic permeability compared to silicon steel contribute to reducing stray losses;
- Corner losses due to flux deviation are absent (see section 5.1.1.3);
- These transformers are less subjective to harmonic currents (see chapter 3) compared to silicon steel (see 5.1.1.2), The core losses of material 2605SA1 are proportional to frequency and maximum flux density:

  $$Pcore\,[\frac{W}{kg}] \sim f^{1.51} \times Bmax^{1.74} \qquad \text{(equation 5.6)}$$

  where,

  f is the frequency [kHz]

  Bmax is the maximum flux density [T]
- The amorphous metal core must be conditioned prior to its installation in transformers and the application of the windings (Figure 5-9). The metal has to be heated above its Curie temperature and then cooled slowly over some hours in the presence of a conditioning DC magnetic field. This then orientates the magnetic domains in the amorphous material. This procedure adds to the cost of manufacturing such transformers. The 'wound core' technology in case of the amorphous material needs field anneal in order to come to maximum performance. Therefore the cores will undergo heat treatment at 340-360°C. The cycle consists in a heat up phase, soak time (1 hour) and cooling phase (no forced cooling) that can take up to 5 or 6 hours (according to core size and oven load).;
- Low resistance to external stresses. In silicon sheet technology, once the magnetic circuit has been installed, it is rigid, and acts as a mechanical support on which all the transformer elements rest. In amorphous technology, the circuit elements are closed at the bottom-end. This is a fragile area, which must not be subjected to any stress. The impact of own weight on stress in the core has also to be avoided[122].

Potential barriers for up-take:

Amorphous transformers are significantly larger in size and inevitably have a higher purchase price.

No production capacity is available in Europe so far for material production and transformer manufacturers need to adapt their production prices.

Technical development are necessary in most of European company to fullfill completely European standard and IEC standard regarding ability to withstand short circuit tests (According to T&D Europe at stakeholder meeting).

[121] M.J. Heathcote (2007): 'J&P Transformer Book', p. 50, ISBN 978-0-7506-8164-3

[122] CIRED (2009-1): Bertrand JARRY, Patrick LAUZEVIS, Pierre LAGACHE, Michel SACOTTE 'AMORPHOUS SHEET CORE TRANSFORMERS UNDER EXPERIMENTATION ON THE ERDF NETWORK', CIRED 2009 conference proceedings.

According to T&D Europe at stakeholder meeting (May 2010), European manufacturers face difficulties to produce compliant transformers above 1 MVA rated power.).
Industrial end users might hesitate procuring these transformers as long as this uncertainty exists and/or is communicated by trusted European brands.
In Asia however larger (1000-2000 kVA) dry-type and liquid-immersed transformers are produced that passed the short circuit test with similar standards.
One local Amorphous Metal Dry-type Transformer (AMDRT) manufacturer obtained national patent in China (patent No. 99225846.4).
Long time reliability for three phase transformers as demanded by European utilities is not demonstrated on European networks(According to T&D Europe at stakeholder meeting).
Allthough amorphous transformers are on the market since the early 90ies (see 2.2.6.9). For amorphous transformers still some new patents are filed. A search for European Patents related to 'amorphous transformers' results in 36 patents[123]. In the period 2005-2009 still four relevant patents for liquid-filled and/or dry type transformers were filed. This shows that the R&D to cover above mentioned problems is still active.

Quantitative performance data used in this study:
AMT transformers *can surpass class A0 no-load requirements at least by up to 60 %*, e.g. 195 Watt compared to 430 Watt class A0 requirement for a 400 kVA transformer[124]. Especially at low load factors this is an advantage to increase transformer efficiency, see Figure 5-11.

[123] http://ep.espacenet.com/
[124] CIRED (2009-1): Bertrand JARRY, Patrick LAUZEVIS, Pierre LAGACHE, Michel SACOTTE 'AMORPHOUS SHEET CORE TRANSFORMERS UNDER EXPERIMENTATION ON THE ERDF NETWORK', CIRED 2009 conference proceedings

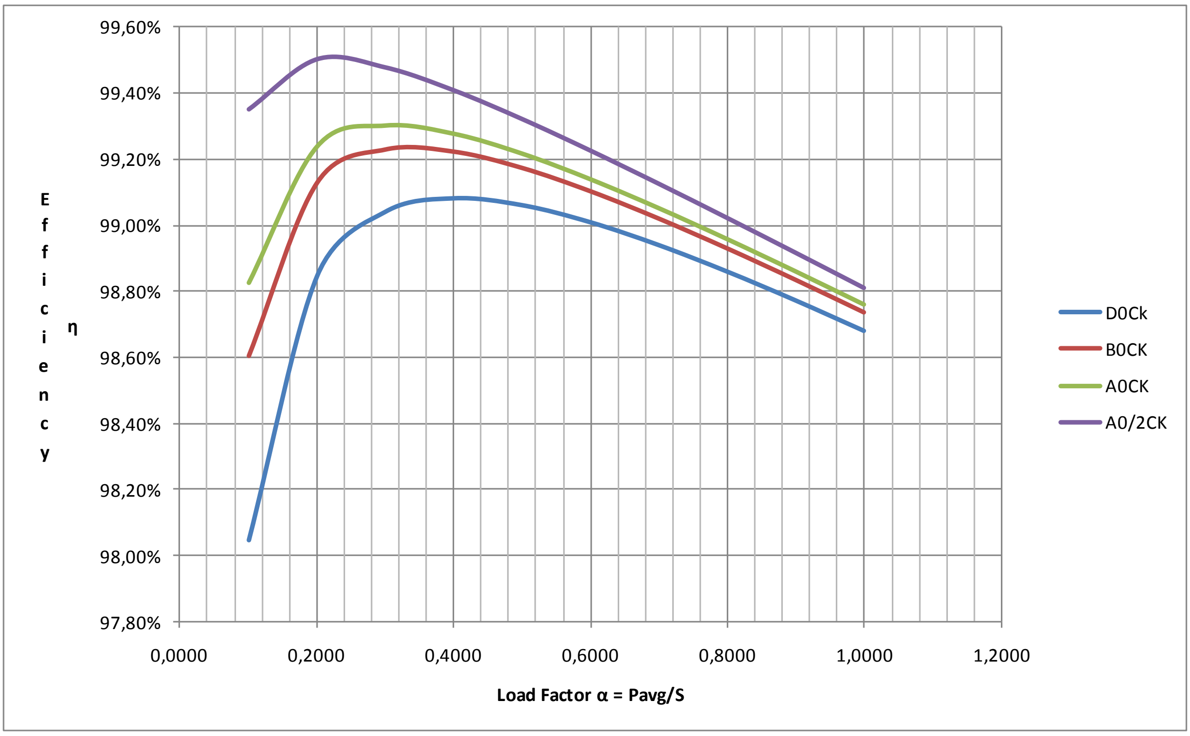

Figure 5-11 Transformer efficiency versus load factor (Pavg/S) according to EN 50464-1 no-load and load loss classes extended with class A0/2 for a 400 kVA transformer.

Quantitative price data used in this study:
On the European market the 400 kVA transformers are not commonly produced, hence it is difficult to obtain a reliable price.
400 kVA AMT - Ck price data was reported more expensive between 130 % and 230 % compared to a D0Ck transformer, please note that no-load losses are significantly lower. Data sources consulted were: manufacturers enquiry, prices from the Indian rule making process and a 1999 THERMIE project[125].
When compared to equivalent A0 no-load level minimum prices reported (India) were competitive with silicon steel transformers, only about 16 % more expensive but having on top about halve the no-load losses (comparing minimum prices found). When the production becomes more mature in Europe, prices could become equal (according to Hitachi-METGLAS).
CLASP provided AMT data based on OPS transformer design software and a cost model (report available on the website). The projected results for Bill of Material (BOM) and price are included in Annex E. It is based on the material prices as included in chapter 2 completed with a production cost model in the assumption of a mature European AMT market with competitive prices.
As explained hereafter CLASP data that is used in this study (Table 5-6) was corrected to reflect similar market conditions as those used in this study for silicon steel transformers (see Annex C).
Rationale for this correction:
The CLASP amorphous transformer prices weren't used directly because after analysis their silicon steel designs (Annex E) didn't reflect the European silicon designs (Annex C) and therefore hadn't an equal basis for comparison. For example, CLASP calculated a 400 kVA D0Ck silicon steel transformer with a 662 kg core and 296 kg conductor. The

[125] Energie publication series, 'The scope for energy saving in the EU through the use of energy-efficient electricity distribution transformers', THERMIE FP 5 project report, 1999.

enquiry and market research (Annex E) proved that European designs have in reality only a 469 kg core and 214 kg conductor. For what matters amorphous transformers the CLASP data is in line with literature and analytic calculations performed by the project (available in the project website). An amorphous transformer with similar load losses has a core of 747 kg and 288 kg conductor, which is significantly more compared to a silicon steel transformer with similar load losses (D0, Ck). Therefore, the CLASP could not guarantee to reflect the same market conditions as those obtained for silicon steel transformers (Annex C) and have not an equal basis for comparison. This was discussed with CLASP (8/11/2010) who agreed this and explained that their silicon steel designs were not optimised as they were not the focus of the report. In order to reflect the same market conditions prices included in Annex E were therefore corrected proportional to the BOM data difference and using the CLASP cost model. The results are included in Table 5-6.

The projected no-load losses of amorphous transformers are typically -35 % up to 60 % lower compared to class A0 (see Annex E).

For the 1250 kVA dry-type AMT (11 kV) data is based on tested transformers available in Asia (incl. short circuit test). For confidentiality reasons BOM and design data (11 kV) was not disclosed by the Asian manufacturer. Therefore the BOM and price data were based on the analytical model data and reversed engineering calculations, see Table 5-6 and Table 5-7. The calculation spreadsheet (see project website) uses an analytical model that is explained in section 5.1.2.8 that has been adapted to amorphous metal. The Asian manufacturers informed us that our estimate was slightly lighter. They also informed us that those transformers run at 1.3T mainly for noise reasons, which leads to a slightly heavier design compared to 1.35T as could be used in liquid filled transformers. The design has also been extrapolated to 22 kV because this is an improvement option for Base Case 3 (chapter 4). It should be noted that ABB announced (2010) starting production of dry-type AMT up to 2500 kVA in Germany[126] But more precise product data was unavailable at the time of the study.

[126] http://www.abb.com/cawp/seitp202/fb0fc8bb128af642c12576e9001d139e.aspx

	400 kVA D0Ck(BC 1 oil)		
	min.	CLASP	max.
Ck	135%	141%	230%
Bk	145%	164%	250%
Ak	155%	175%	290%
Ak-20%	NA	211%	250%
	1000 kVA E0Ck(BC 2 oil)		
	min.	CLASP	max.
Ck	NA	173%	NA
Bk	NA	191%	NA
Ak	NA	206%	NA
Ak-20%	NA	262%	NA
	2000 kVA E0Ck(BC 5 oil)		
	min.	CLASP	max.
Ck	NA	156%	NA
Bk	NA	170%	NA
Ak	NA	225%	NA
Ak-20%	NA	NA	NA
	1250 kVA (BC 3 dry-22kV)		
	min.	study	max.
Ak	NA	249%	NA

Table 5-6 AMT projected prices relative to the Base-cases.

Quantitative bill of material data used in this study:
For liquid-immersed base-case transformers BOM data can be found in Annex E, based on CLASP data provided as mentioned before. The CLASP BOM data fitted very well with the analytical model of this study (400 kVA).
Please note that AMT transformers contain substantially more material. Compared to the Base-case 1 (400 kVA-D0Ck) an AMT (Ck) contains about 59 % more core steel, 7 % more copper and 291 % more aluminium conductor material.
Annex E also illustrates that it is perfectly feasible to design Ak AMT transformers with aluminium low voltage windings, which was apparently not possible with silicon steel transformers. This helps AMT transformers with intrinsic heavier cores competing in price with equal load loss class silicon steel designs. When silicon steel transformers uses aluminium coils, the conductor coil window becomes too large which has a negative effect on core losses. This is hard to compensate in other design or material parameters.
For the 1250 kVA dry-type AMT data is based on tested transformers available in Asia (incl. short circuit test) but BOM data was based on the analytical model data and reversed calculations as explained before, see Table 5-7.

HV	losses		Mass				Transformer design parameters			
	P0	Pk	conductor Cu	Resin	Frame	core SA1	Bmax	Afe	J	h/w
kV	W	W	kg	kg	kg	kg	T	mm²	A/mm²	
11 kV	600	Ak-10%	804	91	200	2537	1.3	140000	1.3	1.17
22 kV	640	Ak	774	88	200	2666	1.3	140000	1.4	1.32

Table 5-7 Projected BOM of 1250 kVA amorphous dry type transformer and basic transformer design parameters used

5.1.2.5 Use of transformers with silicon liquid or biodegradable natural esters instead of dry cast resign transformers

Dry cast resin transformers are often used in applications where flammable mineral oil filled transformers are unacceptable or due to environmental concerns about oil leakage. However, dry type transformers might be less efficient and are noisier compared to oil filled or liquid transformers .

Mineral oil, which complies with the specifications of the international standards for insulating oils, IEC publication 60296 – for distribution transformers without special requirements the fire point is about 170 °C.
Recently several alternative liquids have been developed to overcome their disadvantages compared to mineral oil.

Alternative liquids:
Silicon liquids (e.g. Xiameter^{TM}) are synthetic materials, the most well known being polydimethylsiloxane. They have a very high flash point and if made to burn give off less heat compared to organic liquids. They have the unique property of forming a layer of silica on the surface which greatly restricts the availability of air and avoids combustion[127]. Silicone oil, which is self-extinguishing in case of fire. Due to its high fire point above 300 °C it has been classified as a K-liquid according to IEC 61100.
Natural esters (e.g. Envirotemp^{TM}, MIDEL^{TM}) with excellent fire safety were brought on the market in the late 1990s. The fire point (360 °C) and flash point (330 °C) is considerably higher compared to mineral oil (<140 °C flash point). There is no doubt about its biodegradability and it is environmentally safe. Ester, which is non hazardous to water and has a very good biodegradability. Additionally, ester offers high fire safety due to its high fire point and has also been classified as a K-liquid according to IEC 61100. Readily biodegradable according to OECD 301 and fully biodegradable according to IEC 61039.
Note the fire behaviour is only included in the standard on dry type transformers in IEC 60076-11 (see chapter 1). The behaviour of silicon transformer under fire had never been tested under standardisation condition and pressure in the tank could lead to special results. Therefore on update of the IEC 60076-11 standard for oil filled transformers might be needed taking new developments and test results into account.

Price data:
It is assumed that those liquids are about 250 to 700 % more expensive according to the kind of liquid.
This is a valuable improvement options for BC 6 (DER dry type) because they can be replaced for wind turbine applications in environmental sensitive areas with BC 5 filled with biodegradable oil, those data (liquid volume, price) is included in Annex E (CLASP calculated results).

[127] M.J. Heathcote (2007): 'J&P Transformer Book', p. 103, ISBN 978-0-7506-8164-3

Potential barriers for up-take:
The behaviour of silicon transformer under fire had never been tested under standardisation condition and pressure in the tank could lead to special results. Therefore on update of the IEC 60076-11 standard for oil filled transformers might be needed taking new developments and test results into account

Expected Impact:
For dry type industrial transformers (Base-case 3) switching to liquid-immersed transformers is a valuable options, when those alternative liquids proof to provide sufficient fire behaviour resistance.
For dry type DER transformers (Base-case 6) those biodegradable-liquids are for sure the preferential options because the liquid transformers are far more efficient and are less expensive. DER power sources such as wind turbines or PV inverters have themselves a low short circuit power reducing failure and associated fire risk.

5.1.2.6 Reducing transformer noise

The highest efficiency transformers based on HGO-DR have also reported the lowest noise level (see section 5.1.2.3). Oil filled transformers also have lower transformer noise (see section 5.1.2.5). Hence in silicon steel transformers there is no conflict between efficiency and low noise levels.
On the other hand, amorphous transformers reported higher noise levels compared to silicon steel equivalents (see section 5.1.2.4) but this can be solved by the design. Therefore, noise should not be the primary parameter in choosing technology. The main source of noise is within the core, noise of the coil only contributes for greater than 10 MVA according to ISO 76-10 (Statement of the stakeholder meeting).

Potential barriers for up-take
This might are no strict barriers, only in very rare situations where very compact designs are needed where noise cannot be reduced at the housing and by distance. Therefore, noise should not be the primary parameter in choosing technology.

5.1.2.7 Using an oversized transformer when the load factor is close to or above 0.4

The highest efficiency is achieved when the transformer is loaded between 0.2 and 0.4, see chapter 3 section 3.2.1.1.2. Hence, higher efficiencies can also be achieved by switching to a larger size of transformer.
Example:
1000 kVA industry oil transformer loaded α_e = 0.50 and efficiency E0 (1700W) Ck (10500W), which results in 37627 kWh annual loss
A more efficient option is to install instead a 1250 kVA transfo loaded α_e = 0.40 (=0.5x1000/1250) and efficiency E0 (2100W) Ck (13500W), which results in 37062 kWh annual loss.

Conclusion:
It is important to mention this but it will not be calculated any further as such high load factors were not identified in chapter 3 for the base case scenario.

5.1.2.8 Grouped BOM and cost impact on improvement options for base cases transformer types

Scope:

There are several well-established engineering practices and techniques for improving the efficiency of a distribution transformer as described in the previous sections and summarized in Table 5-8.

General Loss-Reduction Interventions for Distribution Transformers

Loss-Reduction Interventions		No-Load Losses	Load Losses	Effect on Price
Decrease Core Losses	Use lower-loss core materials	Lower	No Change*	Higher
	Decrease flux density by increasing core cross-sectional area	Lower	Higher	Higher
	Decrease flux density by decreasing volts/turn	Lower	Higher	Higher
	Decrease flux path length by decreasing conductor cross-sectional area	Lower	Higher	Lower
Decrease Coil Losses	Use lower-loss conductor materials	No Change	Lower	Higher
	Decrease current density by increasing conductor cross-sectional area	Higher	Lower	Higher
	Decrease current path length by decreasing core cross-sectional area	Higher	Lower	Lower
	Decrease current path length by increasing volts/turn	Higher	Lower	Lower

*Amorphous-core materials would result in higher load losses because flux density drops, requiring a larger core volume.

Table 5-8 General Loss-Reduction Interventions for Distribution Transformers (source: DOE)[128].

A transformer design can be made more energy-efficient by improving the materials of construction (e.g., better quality core steel or winding material) and by modifying the geometric configuration of the core and winding assemblies. Core and winding losses are not independent variables of transformer design, but are linked to each other by the heat they generate and by the physical space they occupy. Transformers are designed for a certain temperature rise, resulting from the heat generated by transformer losses during operation. The upper boundary on the temperature increase is a design constraint, based on industry practice and standards. If this temperature limitation is exceeded, it will accelerate the aging process of the insulation and reduce the operating life of the transformer. In addition to the core and winding assemblies, a transformer has other non-electromagnetic elements that may constrain the design of a transformer: the electrical insulation, insulating media (oil for liquid-immersed transformers and air for dry-type transformers), and the enclosure (the tank or case). Once the insulation requirements are set, a transformer design can vary both materials and geometry to reduce the losses.

The conclusion is that making a transformer more efficient (i.e., reducing electrical losses) is a design trade-off. At a given loading point and associated efficiency level, there can be several viable designs that achieve that efficiency level leading to an infinite number of design options. Because of this variety in design options the impact on BOM and cost on base case type transformers as defined in chapter 4 is grouped hereafter to selected improvement efficiency levels.

[128] Technical support document: Energy efficiency program for commercial and industrial equipment: electrical distribution transformers', U.S. Department of Energy (DOE), September 2007

General approach:
The main data source is the manufacturing enquiry, see annex B and C.
The price charged for a transformer by a transformer manufacturer is influenced by their ability to organise (more efficient), design (less material), marketing, pricing policy. This data is more realistic and therefore the subsequent Ecoreports will be based on this data.
In order to double check also analytic model data is added, in which the cost was assumed proportional to the core and conductor material price increase based on weight and type of core material.
Material processes are included in chapter 2, for silicon steel M6 will be used as reference for the base case.
For the sake of simplicity, only the impact on the conductor and core material on the Bill of Material (BOM) will be assessed hereafter. The impact on the BOM of other parts (paper, oil, resign) will therefore be chosen in chapter 6 proportional to the core and conductor material increase. It can also take into account the switch from aluminium to copper, if any, with data in section 5.1.2.1. These simplifications for what matters the Bill of Material are acceptable as chapter 4 already indicated that the environmental impact related to the BOM are very low, the use phase or energy efficiency is far more important.

Data collection from stakeholders:
Stakeholders were asked to complete an enquiry see annex B. The first part of the enquiry is on price impact from the improvement options for different base cases (BC). Chapter 4 indicated that this is a relevant parameter in the Life Cycle Cost (LCC). The second part of the enquiry asks for impact on the Bill of Material (BOM) related to conductor and core material. Chapter 4 has already indicated that this impact is weak, therefore this part has been kept simple as well. Nevertheless the spreading in those basic BOM data indicated that transformer manufacturers uses various strategies to reduce cost and develop a product range, in line with strategies illustrated in Table 5-8 and explained before on the grouped improvement options.

Data collection from transformer design software:
CLASP has provided transformers designed with OPS transformer design software, see Annex E.
Data generation with analytic equations and design samples from literature:
The impact based on core and conductor material changes has also been assessed with extrapolations based on an analytical model based on the main transformer equations as a verification or completion of the manufacturing enquiry data. A similar approach is also known as scaling relationships in transformer manufacturing[129]. The spreadsheets can be downloaded on the project website (www.ecotransformer.org).
Background information on the spreadsheet and used equations:

- It uses the basic transformer 'voltage per turn(V/N)' design formula[130] to calculate the numbers of turns in the primary winding:

$$V/N = 4.44 \times f \times Bmax \times Afe \qquad \text{(equation 5.7)}$$

Where,

Bmax is the maximum flux density [T]
f is the frequency [Hz]
Afe is the core cross-section area [m²]

[129] Technical support document: Energy efficiency program for commercial and industrial equipment: electrical distribution transformers', U.S. Department of Energy (DOE), September 2007, chapter 5.
[130] R. Feinberg, 'Mordern Power Transformer Practice', p.46, Mcmillan Press, 1979, ISBN 0-333-24537-7.

- Afterwards the coil conductor cross-section is calculated (ACu[mm²]) based on the maximum primary current (I), the calculated turns (N), current density (J) [A/mm²] and layers of turns per primary coil in the assumption of rectangular wires;
- in principle all dimensions are defined having the conductor cross section, the height/width of the coil and the cross-section of the core when taking some extra distances into account for: coil support, mechanical constraints, insulation, cooling and thermal constraints. A lumped component model was used to simplify the geometry. Losses were also simplified neglecting: real flux distribution, temperature distribution and stray loss. The additional distances were simplified and chosen proportional to 'space [mm]' and finally core and conductor mass and losses were tuned to existing design samples;
- The power transformer was fine tuned to a 60 MVA sample[131] and the oil filled distribution and industry transformers were fine tuned to a 1000 KVA sample design[132].
- For simplicity and coherence with design samples found in literature all calculations were done with copper conductors. Because the base case transformer (chapter 4) do include also alumium conductors the impact of conductor of the transformer price was reduced. This was done by reducing the conductor price in between aluminium and copper and proportional to it's share in the base transformer (see spreadsheet).
- Green cells are input cells and blue one important calculated results.
- The analytical model assesses the impact on the BOM data proportional to the base case core and conduction mass and also the cost impact proportional to the from the impact on core mass and conductor.
- Finally there were some correction factors introduced to fit with the copper loss and core weight to correct for simplifications and to fit with the design samples.
- The book 'Mordern Power Transformer Practice'[133] contains the description of the analytical model spreadsheets that are available on the project website. Those spreadsheets were used to extrapolate power transformer Bill of Material (BOM) data and dry type amorphous transformer data (section 5.1.2.4).

Note: This method is similar to DOE[134] but focus on no-load and load losses together with core and conductor material as needed for the MEEuP.

Overview of analytical model results:
Calculated results for input in chapter 6 are summarized in Table 5-9 and Table 5-10. Extrapolations to other power ratings can be done using the transformer design scaling relationships as proposed in Table 5-11 (see also chapter 2).

[131] R. Feinberg, 'Mordern Power Transformer Practice', p.70, Mcmillan Press, 1979, ISBN 0-333-24537-7.
[132] Design No. 3/23/2005:1857/1000 available at www.softbitonline.com
[133] R. Feinberg, 'Mordern Power Transformer Practice', p.46, Mcmillan Press, 1979, ISBN 0-333-24537-7.
[134] Technical support document: Energy efficiency program for commercial and industrial equipment: electrical distribution transformers', U.S. Department of Energy (DOE), September 2007, chapter 5.

Si-steel	losses		Mass		Price	Transformer design parameters			
	P0	Pk	conductor	core		Bmax	Afe	J	h/w
grade	W	W	% of ref.	% of ref.	% of ref.	T	mm²	A/mm²	
M150-35S	E0	Ck	100%	100%	100%	1.70	34200	2.44	1.35
M120-23S	D0	Ck	100%	100%	108%	1.7	34200	2.44	1.35
M103-27P	C0	Bk	113%	102%	116%	1.70	34200	2.20	1.41
HiB-DR(M090-23P)	B0	Ak	145%	127%	176%	1.5	40000	1.8	1.37
HiB-DR(M090-23P)	A0	Bk	152%	108%	164%	1.50	34000	1.90	1.69
HiB-DR(M090-23P)	A0	Ak	209%	108%	192%	1.5	32000	1.5	2.03

Table 5-9: Analytic model result for a 1000 kVA oil filled distribution transformer (BC 2 in chapter 4)

Si-steel	losses		Mass		Transformer design parameters			
	P0	Pk	conductor	core	Bmax	Afe	J	h/w
grade	W	W	% of ref.	% of ref.	T	mm²	A/mm²	
M4-CGO M130	100%	100%	100%	100%	1.5	550000	3.1	1.49
M3-CGO M120	85%	100%	115%	93%	1.5	500000	2.9	1.75
M3-CGO M120	70%	100%	179%	78%	1.5	375000	2.3	2.84
HGO-DR M095	50%	100%	303%	64%	1.5	285000	1.77	3.84
M4-CGO M130	100%	85%	133%	99%	1.5	520000	2.5	1.73
M3-CGO M120	85%	85%	140%	97%	1.5	505000	2.4	1.81
M3-CGO M120	70%	85%	223%	80%	1.5	370000	1.9	3.06
HGO-DR M095	50%	85%	385%	66%	1.5	280000	1.45	4.19
M4-CGO M130	100%	75%	172%	100%	1.5	510000	2.0	1.89
M3-CGO M120	85%	75%	195%	95%	1.5	470000	1.85	2.17
M3-CGO M120	70%	75%	340%	80%	1.5	330000	1.4	3.97
HGO-DR M095	50%	75%	551%	68%	1.5	265000	1.1	4.96

Table 5-10: Analytic model result for a 100 MVA oil filled power transformer (BC 4 in chapter 4).

kVA	scaling factor
1000	1.00
400	0.46
1250	1.21
2000	1.79

Table 5-11: Scaling factors $(S1/S2)^{0.75}$ for obtaining other transformer data.

Overview of manufacturer enquiry results:

Two manufacturers enquiries were launched, these results were aggregated and results are included in Annex C and D. Annexes C and D data include the price data that will be used in subsequent tasks.
Please note that for dry-type transformers the load classes were based on the draft standard prEN 50541-1 (see chapter 1) with 22 kV HV winding.
From the power transformer enquiry it can also be seen that the higher the HV winding is the more difficult it is to achieve a higher efficiency, mainly because more insulation distance is required between the windings.

Smaller transformer data:

The data (Table 5-12) for the smaller industrial isolation/separation transformer was deducted from catalogue data, it should be noted that is was within the same volume hence it is probably mainly related to increased use of copper in combination with HiB steel.

model	losses		Mass		Price
	P0	Pk	conductor	core	
	W	W	% of ref.	% of ref.	% of ref.
BC 7	110	750	100%	100%	100%
BAT	110	400	157%	110%	142%

Table 5-12: Improvement options for 16 kVA smaller industrial isolation/separation transformer

Potential barriers for up-take:
Most of these improvement options increase the volume and weight of the transformer, for certain applications with volume constraints this might be a barrier.

5.1.2.9 Improvement options at system level by increasing the MV voltage and having dual or triple windings

Part of the transmission losses are in the MV cables. By increasing the voltage for the same cable cross sectional area (CSA) one can reduce cable losses.
Raising the MV voltage is a strategic and stepwise process, e.g. ERDF has increased the voltage of the MV systems over the years from 11 to 22 kV in order to reduce losses.
This can be done by having transformers that have dual or triple windings at the primary that can be reconfigured to adapt to the voltage.
The product requirement should be that distribution transformers with primary voltage below 20 kV should at least have a dual winding to adapt over time to an increased line voltage.

According to stakeholders the transformer price would be about 20 % higher.

Impact on losses:

- MV Cable assumptions:
  - Assuming average 10 km cable between a distribution transfo and the HV/MV substation
  - Assuming a cable having 0.265 ohm/km resistance, equivalent to MV CABLE TYPE C 33-226with 3x150 mm² Aluminium.
  - No extra cable cost as current cables by default can widthstand up to 25 kV.

- MV cable loading for BC 1 is about 6.5 ampere (=400/11x0.18).

This results in about copper losses (RI^2): $10 \times 0.265 \times 6.5^2 = 113$ Watt
By increasing the voltage by a factor 2 the losses can be reduced by half.

5.1.3 Existing technologies not further considered for BAT

5.1.3.1 Improvement options at system level in reducing transformation steps

Another possibility to reduce losses is on the system level by reducing redundancies within the grid system: i.e. reducing the number of transformers in the grid and increasing capacity utilisation of remaining transformers.

5.1.3.2 Use of silver wires

The electrical conductivity of silver exceeds that of copper, aluminium, and other normal metals at room temperature (25° Celsius). However, silver has a lower melting point, a lower tensile strength, and limited availability. The DOE (US) study[135] found that the use of silver as a conductor is technologically feasible, since distribution transformers with silver windings were built during World War II because of a war-time shortage of copper. However, silver was screened out as a conductor material because it is impracticable to manufacture, install, service and has limited availability. Silver was found unfeasible to use for mass production on the scale necessary for distribution transformers.

5.1.3.3 Use of any particular core form

The most frequently used transformer core form in Europe is the 3-phase 3-limb core (Figure 5-12). Alternatively a 3-phase 5-limb core form (Figure 5-13) is used. This form allows the reduction of the yoke depth by half by providing a return flux path external to the windings but needs more core material and processing. Nevertheless, this reduction in height is sometimes used in large power transformers to limit the transport height.
Also 3-phase hexagonal core form (Figure 5-14) transformers are found on the market[136]. They are available up to 200 kVA with an efficiency class BoCk. Hence, the no-load losses (Po) are improved compared to the base case distribution transformer (see chapter 4). They are wound with three steel bands in each of three sections that are mounted to form a closed and symmetrical cage core. They benefit from lower core losses due to shorter yokes and the absence of core corner loss problems (see section 5.1.1.3). The more cylindrical construction also results in a more compact housing. Technical limitations are that the lowest loss HiB-DR with laser scribing cannot be used (see also 5.1.2.3), because the bended core involves stress relief annealing (see 5.1.2.3), therefore HiB-DR mechanically-scribed domain refined steel should be used. Furthermore the cross section is far from circular which means increased load losses (see 5.1.2.2).
Due to the many engineering trade-offs (see 5.1.2.8) all core forms can lead to efficient designs and they will not be considered as an improvement as such. The hexagonal

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[135] 'Technical support document: Energy efficiency program for commercial and industrial equipment: electrical distribution transformers', U.S. Department of Energy (DOE), September 2007
[136] www.hexaformer.com

core was not analysed in detail because it does not fit with the 400 kVA base transformer on chapter 4.

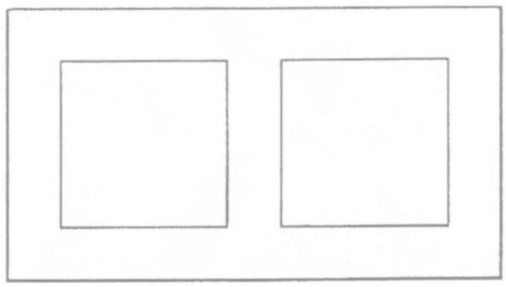

Figure 5-12: The most frequently used 3-phase 3-limb core form in distribution transformers

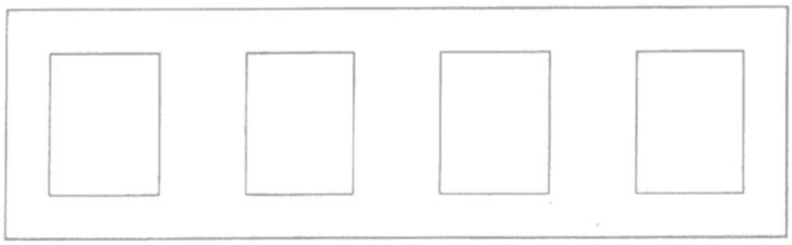

Figure 5-13: A 3-phase 5-limb core form that is sometimes used in large power transformers to reduce transport height

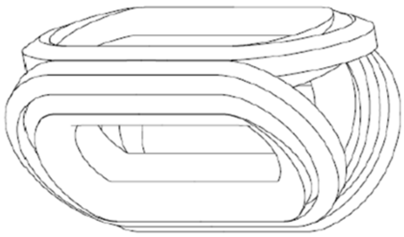

Figure 5-14: A hexagonal core form sometimes used in compact small (<250 kVA) distribution transformers

5.2 Best Not Yet Available Technologies – BNAT

5.2.1 R&D on amorphous metals

Research continues for new materials to reaches saturation at induction levels close to those typical for magnetic steel, for example recently alloy 2605HB1 was introduced (see 5.1.2.4). This would allow more compact cores and smaller-lighter transformers than the current amorphous designs. Other elements are related to the reduction of noise levels.

5.2.2 R&D on silicon steel

The industrial research activities[137] are targeting on one hand on superior GO products with lower losses and higher permeabilities for the demands of more energy-efficient or low noise transformers (Figure 5-15). On the other hand, industrial research is targeting with very high priority on reduction of manufacturing costs. This shall be obtained by more compact processes, by saving energy and resources, and by a more stable production with higher material yield.

Some of the most promising potentials for further improvement of the magnetic properties are:

- More uniform domain wall movement by:
    - smoother surfaces (less pinning sites for Bloch walls).
    - sharper texture (less 90° surface closure domains).
- More efficient domain wall movement by:
    - new coatings with optimised tension.
    - improved laser scribing or mechanical scribing.
    - improved grain structure (generating micrograins, controlling grain shape).

Potentials for reduction of manufacturing costs require to simplify the manufacturing process itself. The conventional production process of GO electrical steel starts in the hot area with steelmaking, continuous casting slabs with e.g. 250 mm thickness and hot rolling to e.g. 2.0 mm thickness and finishes in the cold area with thermal flattening and domain refinement. In nearly every stage until box annealing there are crucial factors for the inhibition system which has to restrain normal grain growth and to control secondary recrystallization. Maximum in-hibition strength is obtained with a homogeneous distribution of particles having diameters in the order of 50 to 100 nm. Processes to shorten this standard process are the following:

- Low temperature slab reheating
- Thin slab casting
- Thin strip casting

Among these various processes the thin slab casting is the most advanced technology for manufacturing GO electrical steel today.

[137] M. HASTENRATH, L. LAHN, R. LEMAITRE: 'New Developments in Manufacturing of GO Electrical Steel', Transformer Research and Asset Management, Cavtat/Croatia, November 12-14, 2009.

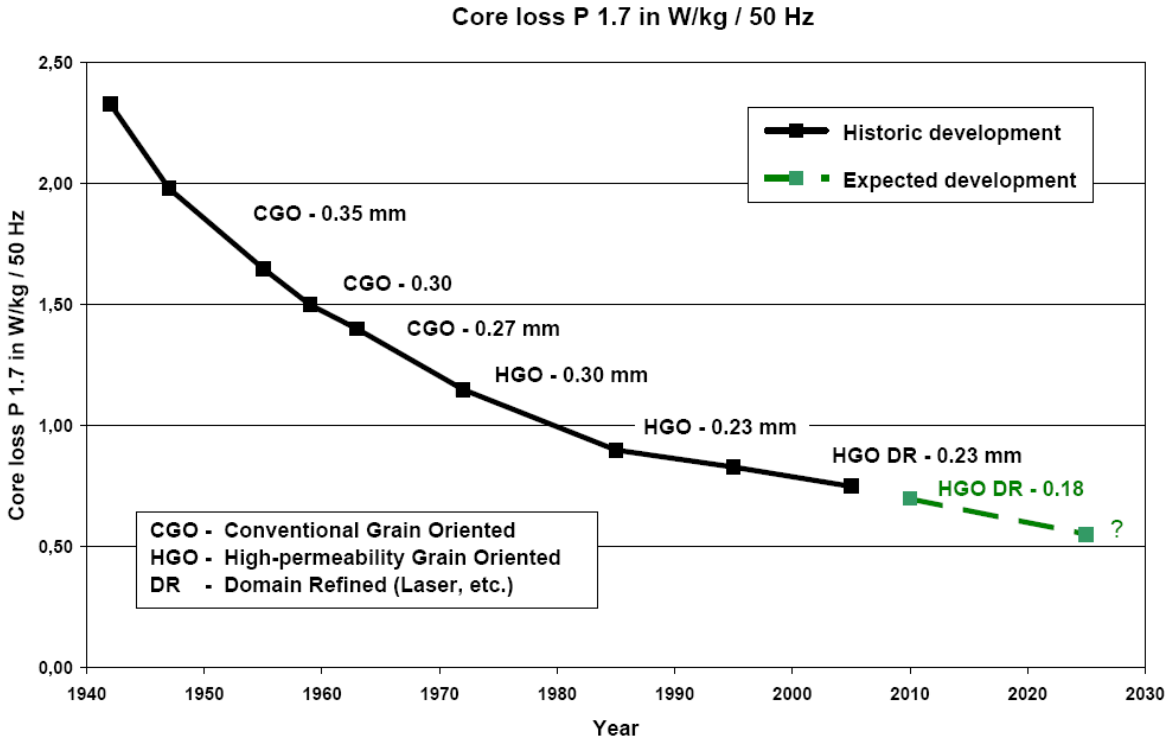

Figure 5-15 History and expected developments of core losses

5.2.3 R&D on microcrystalline steel

Another approach[138] is the production of high silicon and aluminium-iron alloys by rapid solidification in much the same matter as for amorphous steel without the high content of glass forming material (boron and silicon).

5.2.4 Using superconducting technology

Superconducting technologies[139] are being applied to power transformers in the development of so-called high-temperature superconducting (HTS) transformers. In HTS transformers, the copper and aluminium in the windings would be replaced by superconductors. In the field of superconductors, high temperatures are considered to be in the range of –121 to –93°C, which represents quite a significant deviation in the operating temperatures of conventional transformers. At these temperatures, insulation of the type currently used in transformers would not degrade in the same manner. Using superconducting conductors in transformers requires advances in cooling, specifically refrigeration technology directed toward use in transformers. The predominant cooling medium in HTS development has been liquid nitrogen, but some other mediums have been investigated as well. Transformers built using HTS technology would reportedly be of reduced size and weight (10-30% lower weight) and capable of overloads without experiencing "loss of life" due to insulation degradation (25% overload without accelerated ageing), instead using an increased amount of the

[138] M.J. Heathcote (2007): 'J&P Transformer Book', p. 52, ISBN 978-0-7506-8164-3
[139] 'Technical support document: Energy efficiency program for commercial and industrial equipment: electrical distribution transformers', U.S. Department of Energy (DOE), September 2007

replaceable coolant. An additional benefit would be an increase in efficiency of HTS transformers over conventional transformers due to the fact that resistance in superconductors is virtually zero, thus eliminating the I^2R loss component of the load losses (about 50% lower load losses compared to Ak level, operational efficiency about 99.3-99.5%). The I^2R loss component is usually over 90% of the load loss in distribution transformers.

High hopes are connected with the application of superconductors. It is expected that the weight of windings will be smaller. Depending on the cost of the superconductor material, this may pay off. Currently the price of such a transformer is about 150-200% higher than traditional transformer. Furthermore the use of these superconductive transformers entails additional maintenance costs (cryogenic system). Figure 5-16 shows the expected evolution in cryogenic refrigeration cost reduction.

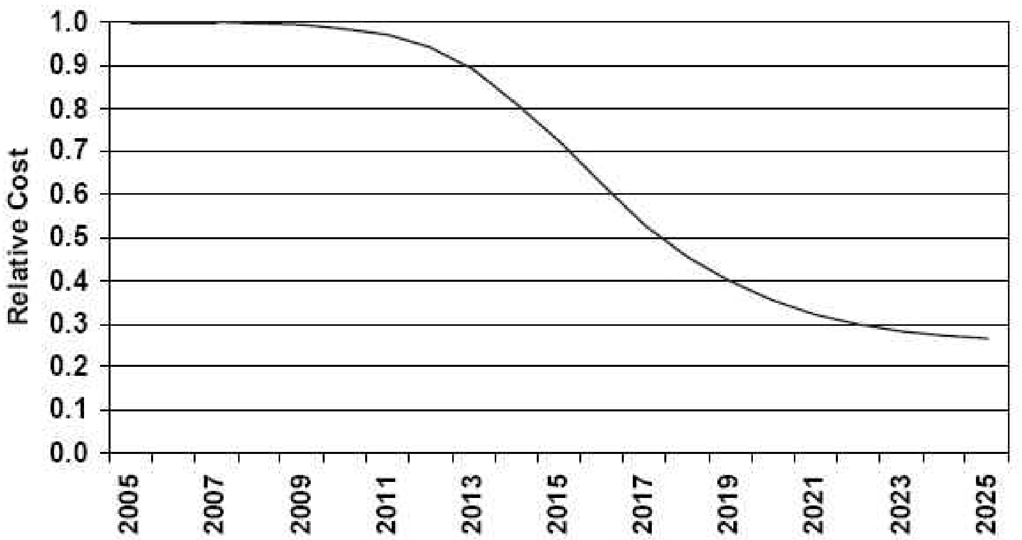

Figure 5-16: Expected reduction trends in cry refrigeration cost (DOE, 2003[140])

However, currently the application of superconducting technology does not yet seem to be economically feasible and its introduction into the European market seems to be far off.
InEurope some prototype superconducting distribution transformers have been built[141]. One company has developed a nitrogen-cooled 630 kVA high temperature superconductor (HTS) transformer, which was installed in the Swiss electricity supply network in 1997. This is a single-phase transformer, and considerable engineering problems are reported in producing three-phase versions. It is widely agreed that superconductivity will always remain much more expensive for power distribution transformers than conventional technology. The most promising areas appear to be in specialist applications, particularly traction transformers, where increasingly large transformers are required for train motors in railway networks.
It remains speculative that this technology will ever appear in distribution transformer markeT

[140] Source US DOE (2003) A high field pulsed solenoid for liquid metal target studies
[141] Energie publication series, 'The scope for energy saving in the EU through the use of energy-efficient electricity distribution transformers', THERMIE FP 5 project report, 1 999.

5.2.5 Using smart grid technology to switch off an by-pass transformers off peak load (system level)

This can reduce the losses by reducing the availability factor (AF) (chapter 3). This requires the grid to be automated and renovated in a so-called smart grid[142]. Potential barriers for uptake are: impact on grid protection unknown, no smart grid available yet, requires SF6 containing switches[143], should be implemented at system level and not at product level. What is done these days is mainly either permanent paralleling or single unit in, based in an overall loss efficiency rationale. Active switching, based in load measurement, rarely happens and is a good, obvious and easily implemented idea.
Smart Grid Technology is a very general and relevant topic, probably best addressed at an overall grid optimisation level, incorporating lines, SCADA and switchgear automation, moving focus from security of supply to loss efficiency, rather than in a context of transformer focus only. DSOs and TSOs face these days rigid availability focused standards/benchmarking, potentially leading to excessive use of no-load loss consumption in idling transformer/generator plant and inefficient operational network conditions. I.e. the view is: The topic is relevant in an ecodesign but perhaps not in a transformer context.

5.2.6 Recover the waste heat of the transformer to heat the substation or any other building (system level)

The primary purpose of transformers is not heating, nevertheless heat could be recovered in some cases to heat the building. Nevertheless they could not be seen as an efficient method of heating a room than dedicated heating appliances. More specifically, the transformer location is often inefficient (e.g. outdoor). Increasing the transformer temperature would increase copper losses (see also section 5.1.2.1) and is not beneficial for the insulation material life time either(see also section 5.1.2.5 on insulation material). Moreover, electrical heating itself is inefficient compared to other forms of heating (e.g. gas or heat pumps) and the heating is unnecessary in the summer period and may even result in increased cooling needs. Heat pumps allow to heat a room with typically 66 % less need for electrical energy compared to resistive electrical heating.
Nevertheless, the UK Market Transformation Programme sometimes recommends using correction factors to take into account what they call the "heat replacement effect". But even these factors remove only 20 to 30% of the estimated savings in energy costs and CO2 emissions, meaning that the balance of savings achieved is still substantial both for the consumer and for the environment.

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[142] European Technology Platform SmartGrids, 'STRATEGIC RESEARCH AGENDA FOR EUROPE'S ELECTRICITY NETWORKS OF THE FUTURE', version 2007.

[143] Sina Wartmann and Jochen Harnisch, 'REDUCTIONS OF SF6 EMISSIONS FROM HIGH AND MEDIUM VOLTAGE ELECTRICAL EQUIPMENT IN EUROPE', Final Report to CAPIEL, 28 June 2005

CHAPTER 6 IMPROVEMENT POTENTIAL

Scope: Identify design options, their monetary consequences in terms of Life Cycle Cost for the user, their environmental costs and benefits, their economic and possible social impacts, and pinpointing the solution with the Least Life Cycle Costs (LLCC) and the Best Available Technology (BAT). The assessment of monetary Life Cycle Costs is relevant to indicate whether design solutions might impact the total user's expenditure over the total product life (purchase, operating, end-of-life costs, etc.). The distance between the LLCC and the BAT indicates —in a case a LLCC solution is set as a minimum target— the remaining space for product-differentiation (competition). The BAT indicates a short- to medium-term target that would probably be more subject to promotion measures than to restrictive action. The BNAT indicates long-term possibilities and helps to define the exact scope and definition of possible measures. The intermediate options between the LLCC and the BAT have to be described, and their impacts assessed.

Summary:
As accomplished in Task 4, the EcoReport tool is used in order to assess environmental and economic impacts of the base-case with improvement options. The improvement options are defined in Task 5 with assistance from stakeholders providing input with an inquiry. With some exceptions, the improvement options prove to be economically superior and more energy efficient. However, these improvement options are inferior regarding certain environmental impacts related to increased material use, such as waste, particulate matter, and eutrophication.

A sensitivity analysis is conducted to examine the effect of assumptions made throughout the text on final results. It is concluded that while the results do change in absolute numbers, generally the results remain the same relative to the base-case. Therefore, it confirms that the results obtained are robust and not significantly dependent upon input assumptions. The factors investigated include:

- Load factor;
- Load form factor (for DER transformers);
- Lifetime;
- Electricity price;
- Transformer price;
- Discount rate;
- Installed stock.

6.1 Identification of design options

Scope: Available design options should be identified by investigating and assessing the environmental impact and LCC of each suggested design option against the Base-Case (using MEEuP EcoReport):

- The design option(s) should not have a significant variation in the functionality and in the primary or secondary performance parameters compared to the Base-Case and in the product-specific inputs.

- The design option(s) should have a significant potential for improvement regarding at least one of the following ecodesign parameters without deteriorating others: the consumption of energy, water and other resources, use of hazardous substances, emissions to air, water or soil, weight and volume of the product, use of recycled material, quantity and nature of consumables needed for proper use and maintenance, ease for reuse and recycling, extension of lifetime or amounts of waste generated.
- The design option(s) should not entail excessive costs. Impacts on the manufacturer should be investigated regarding redesign, testing, investment and/or production costs, including economy of scale, sector-specific margins and market structure, and required time periods for market entrance of the design option(s) and market decline of the current product. The assessment of the monetary impact for categories of users (e.g. by income level, budget availability, geographical location) includes the estimation of the possible price increase due to implementation of the design option, either by looking at prices of the product on the market and/ or by applying a production cost model with sector-specific margins.

It should be described for the identified design option(s):
- if Member State, Community or Third Country legislation and/or standards are available regarding the design option(s);
- how market forces may address the design option(s);
- how large the disparity is in the environmental performance of the product available on the market with equivalent functionality compared to the design option(s).

6.1.1 Option 1: More material, higher grade steel, amorphous steel, and replacing aluminium with copper windings

In accordance with responses received regarding improvement options, improved energy efficiency often is a result of a mix between more material, higher grade steel, amorphous steel, and replacing aluminium with copper windings. The balance and combination of these parameters is the choice of manufacturers, and provides the variety of designs seen on the market today. The averaged results of the stakeholder inquiry are seen in Annexes C and D. The tables below apply the results to the base-case bill of materials and loss characteristics, defining the improvement options.

In each table, the base-case is given as the least efficient model. The improvement options are defined by using the relative increases and changes in core and conductor material, specified by stakeholders with the values seen in Annexes C and D. The mass of other materials is increased proportionally to the total mass increase of the core and conductive material combined. Additionally, it is assumed that product density remains constant in order to estimate volume of the improvement options. Lastly, price increases are reflected with the absolute or relative values supplied by stakeholders, depending upon the case.

Unless explicitly marked with an asterisk, the base-cases and improvement options below use silicon steel for the core. The notation of “A+” for either load or no-load losses signifies losses that go beyond the highest accepted standard.

As the tables below contain significant amounts of data, original spreadsheets are posted on the project website at www.ecotransformer.org to facilitate understanding.

6.1.1.1 Improvement options for BC 1: Distribution transformer 400 kVA

Table 6-1: BC 1 improvement options input data

	D0Ck	C0Ck		B0Bk		A0Ck		A0Ak		A0+Ck*		A0+Bk*		A0+Ak*		A0+Ak+*	
		relative	absolute	relative	absolute	relative	absolute	relative	absolute	relative	absolute	relative	absolute	relative	absolute	relative	absolute
Core Steel (kg)	468.70	1.12	524.94	1.22	571.81	1.35	632.75	1.45	679.62		747.00		910.00		865.00		851.00
Aluminium wire (kg)	21.44	1.06	22.73	1.44	30.87	1.37	29.37	2.07	44.38		82.00		88.00		123.00		0.00
Copper wire (kg)	144.72	1.06	153.40	1.44	208.40	1.37	198.27	2.07	299.57		206.00		255.00		336.00		723.00
Copper sheet (kg)	48.24	1.06	51.13	1.44	69.47	1.37	66.09	2.07	99.86	1.59	76.88	1.94	93.66	1.85	89.03	1.82	87.59
Tank (kg)	266.70	1.10	293.68	1.29	343.78	1.36	361.71	1.64	438.61	1.63	434.79	1.97	526.37	2.09	556.19	2.48	661.22
Paper (kg)	16.00	1.10	17.61	1.29	20.62	1.36	21.70	1.64	26.31	1.63	26.08	1.97	31.57	2.09	33.36	2.48	39.66
Ceramic (kg)	6.02	1.10	6.63	1.29	7.76	1.36	8.16	1.64	9.90	1.63	9.81	1.97	11.88	2.09	12.55	2.48	14.92
Oil (kg)	265.50	1.10	292.36	1.29	342.24	1.36	360.09	1.64	436.64	1.63	432.84	1.97	524.01	2.09	553.70	2.48	658.25
Cardboard (kg)	3.65	1.10	4.02	1.29	4.71	1.36	4.96	1.64	6.01	1.63	5.96	1.97	7.21	2.09	7.62	2.48	9.06
Plastics (kg)	2.05	1.10	2.25	1.29	2.64	1.36	2.78	1.64	3.37	1.63	3.34	1.97	4.04	2.09	4.27	2.48	5.07
Wood (kg)	4.38	1.10	4.83	1.29	5.65	1.36	5.95	1.64	7.21	1.63	7.15	1.97	8.65	2.09	9.14	2.48	10.87
Powder coating/Paint (kg)	5.79	1.10	6.37	1.29	7.46	1.36	7.85	1.64	9.52	1.63	9.43	1.97	11.42	2.09	12.07	2.48	14.35
Total (kg)	1 253.18		1 379.97		1 615.42		1 699.66		2 060.98		2 041.28		2 471.81		2 601.94		3 074.99
Volume (m^3)	2.11	1.10	2.32	1.29	2.72	1.36	2.86	1.64	3.47	1.63	3.44	1.97	4.16	2.08	4.38	2.45	5.18
P_0 (W)	750.00		610.00		520.00		430.00		430.00		196.00		219.00		219.00		216.00
P_k (W)	4 600.00		4 600.00		3 850.00		4 600.00		3 250.00		4 554.00		3 898.00		3 324.00		2 508.00
Electricity losses (kWh/year)	7 858.72		6 632.32		5 633.80		5 055.52		4 677.31		2 992.79		3 010.49		2 849.68		2 594.79
Product price (€/unit)	6 122.05	1.05	6 428.15	1.19	7 285.24	1.16	7 101.58	1.42	8 693.31	1.41	8 632.09	1.64	10 040.17	1.75	10 713.59	2.11	12 917.53

* amorphous steel

The analysis for these improvement options is conducted using the following constants:

Table 6-2: BC 1 improvement options constants

Load form factor (Kf)	1.073
Power factor (Pf)	0.9
Availability factor (Af)	1
Load factor (α)	0.15
Lifetime	40
Electricity rate (€/kWh)	0.078
Annual sales (m)	0.1404
EU stock (m)	2.25
Discount rate	4%
Landfill	1%

6.1.1.2 Improvement options for BC 2: Oil-immersed industry transformer 1 MVA

Table 6-3: BC 2 improvement options input data

	E0Ck	C0Ck		B0Bk		A0Ck		A0Ak		A0+Ck*		A0+Bk*		A0+Ak*		A0+Ak+*	
		relative	absolute	relative	absolute	relative	absolute	relative	absolute	relative	absolute	relative	absolute	relative	absolute	relative	absolute
Core Steel (kg)	882.20	1.14	1 005.71	1.21	1 067.46	1.27	1 120.39	1.48	1 305.66		1 519.00		1 683.00		1 693.00		1 665.00
Aluminium wire (kg)	64.32	1.16	74.61	1.63	104.84	1.54	99.05	2.23	143.43		217.00		260.00		324.00		0.00
Copper wire (kg)	364.48	1.16	422.80	1.63	594.10	1.54	561.30	2.23	812.79		585.00		664.00		809.00		1 788.00
Tank (kg)	601.69	1.15	689.86	1.35	810.70	1.36	817.28	1.73	1 038.10	1.77	1 065.23	1.99	1 196.49	2.16	1 297.01	2.63	1 584.77
Paper (kg)	25.86	1.15	29.65	1.35	34.85	1.36	35.13	1.73	44.62	1.77	45.79	1.99	51.43	2.16	55.75	2.63	68.12
Ceramic (kg)	5.28	1.15	6.06	1.35	7.12	1.36	7.18	1.73	9.12	1.77	9.36	1.99	10.51	2.16	11.39	2.63	13.92
Oil (kg)	493.90	1.15	566.28	1.35	665.47	1.36	670.87	1.73	852.13	1.77	874.40	1.99	982.15	2.16	1 064.65	2.63	1 300.87
Cardboard (kg)	8.92	1.15	10.23	1.35	12.02	1.36	12.12	1.73	15.40	1.77	15.80	1.99	17.75	2.16	19.24	2.63	23.50
Powder coating/Paint (kg)	4.46	1.15	5.11	1.35	6.01	1.36	6.05	1.73	7.69	1.77	7.89	1.99	8.86	2.16	9.61	2.63	11.74
Total (kg)	2 451.12		2 810.31		3 302.57		3 329.38		4 228.93		4 339.47		4 874.19		5 283.64		6 455.92
Volume (m^3)	3.20	1.15	3.67	1.35	4.31	1.36	4.35	1.73	5.52	1.77	5.67	1.99	6.36	2.16	6.90	2.63	8.43
P_0 (W)	1 700.00		1 100.00		940.00		770.00		770.00		383.00		413.00		417.00		411.00
P_k (W)	10 500.00		10 500.00		9 000.00		10 500.00		7 600.00		10 779.00		9 096.00		7 789.00		5 992.00
Electricity losses (kWh/year)	27 168.43		21 912.43		18 757.05		19 021.63		15 631.00		15 957.71		14 252.77		12 759.69		10 606.11
Product price (€/unit)	10 926.00	1.11	12 127.86	1.26	13 766.76	1.24	13 548.24	1.53	16 716.78	1.73	18 901.98	1.91	20 868.66	2.06	22 507.56	2.62	28 626.12

* amorphous steel core

Table 6-4: BC 2 improvement options constants

Load form factor (Kf)	1.096
Power factor (Pf)	0.9
Availability factor (Af)	1
Load factor (α)	0.3
Lifetime	25
Electricity rate (€/kWh)	0.078
Annual sales (m)	0.0432
EU stock (m)	0.504
Discount rate	4%
Landfill	1%

6.1.1.3 Improvement options for BC 3: Dry-type industry transformer 1.25 MVA

Table 6-5: BC 3 improvement options input data

	C0Bk	B0Bk		A0Bk		A0Ak		A0+Ak*	
		relative	absolute	relative	absolute	relative	absolute	relative	absolute
Core Steel (kg)	1 872.96	1.11	2 078.98	1.23	2 303.74	1.36	2 547.22		2 666.00
Aluminium wire (kg)	355.45	1.05	373.22	1.15	408.77	1.47	522.51		0.00
Copper wire (kg)	104.83	1.05	110.07	1.15	120.55	1.47	154.09		774.00
Tank (kg)	118.79	1.10	130.45	1.21	144.24	1.38	164.14		200.00
Resin (kg)	145.96	1.10	160.29	1.21	177.23	1.38	201.67		88.00
Ceramic (kg)	60.78	1.10	66.74	1.21	73.80	1.38	83.98	1.43	87.21
Powder coating/Paint (kg)	1.38	1.10	1.52	1.21	1.68	1.38	1.91	1.43	1.98
Plastics (kg)	16.12	1.10	17.70	1.21	19.57	1.38	22.27	1.43	23.12
Total (kg)	2 676.26		2 938.97		3 249.56		3 697.78		3 840.32
Volume(m^3)	2.94	1.10	3.22	1.21	3.56	1.38	4.06	1.43	4.21
P_0 (W)	2 800.00		2 100.00		1 800.00		1 800.00		638.00
P_k (W)	13 000.00		13 000.00		13 000.00		11 000.00		10 708.00
Electricity losses (kWh/year)	39 727.39		33 595.39		30 967.39		28 629.02		18 108.50
Product price (€/unit)	16 333.07	1.07	17 476.38	1.15	18 783.03	1.50	24 499.60	2.49	40 669.34

* amorphous steel core

Table 6-6: BC 3 improvement options constants

Load form factor (Kf)	1.096
Power factor (Pf)	0.9
Availability factor (Af)	1
Load factor (α)	0.3
Lifetime	30
Electricity rate (€/kWh)	0.078
Annual sales (m)	0.008047
EU stock (m)	0.1088
Discount rate	4%
Landfill	2.3%

6.1.1.4 Improvement options for BC 4: Power transformer 100 MVA

Power transformer of 100 MVA, 132/33 kV. Data from stakeholder inquiry found in Annexe D.

Table 6-7: BC 4 improvement options input data (Part 1)

	41-326	34-326		34-277		34-228		28-326		28-277	
		relative	absolute	relative	absolute	relative	absolute	relative	absolute	relative	absolute
Core Steel (kg)	39 486.67	0.93	36 722.60	0.99	39 091.80	1.00	39 486.67	0.93	36 722.60	0.97	38 302.07
Copper wire (kg)	17 487.84	1.15	20 111.01	1.33	23 258.82	1.72	30 079.08	1.15	20 111.01	1.40	24 482.97
Copper sheet (kg)	1 204.75	1.15	1 385.46	1.33	1 602.32	1.72	2 072.17	1.15	1 385.46	1.40	1 686.65
Tank (kg)	11 307.00	1.00	11 314.73	1.10	12 429.10	1.23	13 922.65	1.00	11 314.73	1.11	12 529.91
Paper (kg)	504.54	1.00	504.88	1.10	554.61	1.23	621.25	1.00	504.88	1.11	559.10
Ceramic (kg)	472.33	1.00	472.65	1.10	519.20	1.23	581.59	1.00	472.65	1.11	523.41
Oil (kg)	26 848.48	1.00	26 866.86	1.10	29 512.92	1.23	33 059.37	1.00	26 866.86	1.11	29 752.31
Powder coating/Paint (kg)	391.72	1.00	391.99	1.10	430.59	1.23	482.34	1.00	391.99	1.11	434.09
Wood (kg)	2 672.74	1.00	2 674.57	1.10	2 937.98	1.23	3 291.03	1.00	2 674.57	1.11	2 961.81
Total (kg)	100 376.05		100 444.76		110 337.33		123 596.14		100 444.76		111 232.32
Volume (m^3)	188.76	1.00	188.89	1.10	207.49	1.23	232.43	1.00	188.89	1.11	209.18
P_0 (W)	40 500.00		34 425.00		34 425.00		34 425.00		28 350.00		28 350.00
P_k (W)	326 000.00		326 000.00		277 100.00		228 200.00		326 000.00		277 100.00
Electricity losses (kWh/year)	519 271.78		466 054.78		441 381.01		416 707.24		412 837.78		388 164.01
Product price (€/unit)	755 843.00	1.06	801 193.58	1.20	907 011.60	1.60	1 209 348.80	1.19	899 453.17	1.39	1 050 621.77

Table 6-8: BC 4 improvement options input data (Part 2)

	41-326	28-228		20-326		20-277		20-228	
		relative	absolute	relative	absolute	relative	absolute	relative	absolute
Core Steel (kg)	39 486.67	0.95	37 512.33	0.78	30 799.60	0.80	31 589.33	0.80	31 589.33
Copper wire (kg)	17 487.84	1.95	34 101.28	1.79	31 303.23	2.23	38 997.88	3.40	59 458.65
Copper sheet (kg)	1 204.75	1.95	2 349.26	1.79	2 156.50	2.23	2 686.59	3.40	4 096.15
Tank (kg)	11 307.00	1.27	14 374.50	1.10	12 488.64	1.26	14 240.58	1.64	18 491.03
Paper (kg)	504.54	1.27	641.41	1.10	557.26	1.26	635.44	1.64	825.10
Ceramic (kg)	472.33	1.27	600.46	1.10	521.69	1.26	594.87	1.64	772.42
Oil (kg)	26 848.48	1.27	34 132.29	1.10	29 654.31	1.26	33 814.30	1.64	43 906.98
Powder coating/Paint (kg)	391.72	1.27	497.99	1.10	432.66	1.26	493.35	1.64	640.60
Wood (kg)	2 672.74	1.27	3 397.83	1.10	2 952.06	1.26	3 366.18	1.64	4 370.89
Total (kg)	100 376.05		127 607.37		110 865.94		126 418.52		164 151.16
Volume (m^3)	188.76	1.27	239.97	1.10	208.49	1.26	237.73	1.64	308.69
P_0 (W)	40 500.00		28 350.00		20 250.00		20 250.00		20 250.00
P_k (W)	326 000.00		228 200.00		326 000.00		277 100.00		228 200.00
Electricity losses (kWh/year)	519 271.78		363 490.24		341 881.78		317 208.01		292 534.24
Product price (€/unit)	755 843.00	2.00	1 511 686.00	1.80	1 360 517.40	2.15	1 625 062.45	2.50	1 889 607.50

Table 6-9: BC 4 improvement options constants

Load form factor (Kf)	1.08
Power factor (Pf)	0.9
Availability factor (Af)	1
Load factor (α)	0.2
Lifetime	30
Electricity rate (€/kWh)	0.078
Annual sales (m)	0.003046
EU stock (m)	0.06435
Discount rate	4%
Landfill	1.0%

6.1.1.5 Improvement options for BC 5: DER transformer oil-immersed 2 MVA

Table 6-10: BC 5 improvement options input data

	E0Ck	C0Ck		A0Ak		A0+Ck*		A0+Bk*		A0+Ak*	
		relative	absolute	relative	absolute	relative	absolute	relative	absolute	relative	absolute
Core Steel (kg)	1 715.47	1.06	1 818.40	1.18	2 024.25		3 298.00		3 469.00		3 698.00
Aluminium wire (kg)	190.44	1.11	211.38	2.21	420.86		161.00		236.00		0.00
Copper wire (kg)	542.74	1.11	602.44	2.21	1 199.46		574.00		813.00		2 003.00
Copper sheet (kg)	219.00	1.11	243.09	2.21	483.99	1.92	421.03	2.02	442.86	2.16	472.10
Tank (kg)	1 113.01	1.08	1 199.65	1.55	1 722.54	1.65	1 833.16	1.85	2 053.62	2.33	2 591.34
Paper (kg)	10.31	1.08	11.11	1.55	15.95	1.65	16.98	1.85	19.02	2.33	24.00
Oil (kg)	800.30	1.08	862.61	1.55	1 238.59	1.65	1 318.13	1.85	1 476.64	2.33	1 863.29
Cardboard (kg)	10.62	1.08	11.44	1.55	16.43	1.65	17.49	1.85	19.59	2.33	24.72
Nomex (kg)	21.69	1.08	23.38	1.55	33.56	1.65	35.72	1.85	40.01	2.33	50.49
Powder coating/Paint (kg)	4.32	1.08	4.66	1.55	6.69	1.65	7.12	1.85	7.97	2.33	10.06
Total (kg)	4 627.89		4 988.16		7 162.32		7 682.62		8 577.72		10 736.99
Volume (m^3)	4.02	1.08	4.33	1.55	6.21	1.66	6.67	1.85	7.44	2.32	9.32
P_0 (W)	3 100.00		2 100.00		1 450.00		812.00		857.00		914.00
P_k (W)	21 000.00		21 000.00		15 000.00		20 927.00		15 057.00		10 107.00
Electricity losses (kWh/year)	59 093.50		50 333.50		35 514.50		38 939.60		30 406.51		23 377.70
Product price (€/unit)	18 248.38	1.16	21 168.12	1.68	30 657.28	1.56	28 467.47	1.70	31 022.25	2.25	41 058.85

* amorphous steel core

Table 6-11: BC 5 improvement options constants

Load form factor (Kf)	1.5
Power factor (Pf)	0.9
Availability factor (Af)	1
Load factor (α)	0.25
Lifetime	25
Electricity rate (€/kWh)	0.3
Annual sales (m)	0.00058
EU stock (m)	0.004
Discount rate	4%
Landfill	1.0%

6.1.1.6 Improvement options for BC 6: DER transformer dry-type 2 MVA

Table 6-12: BC 6 improvement options input data

	C0Bk	**B0Bk**		**A0Ak**	
		relative	**absolute**	**relative**	**absolute**
Core Steel (kg)	3 568.82	1.24	4 425.34	1.34	4 782.22
Aluminium wire (kg)	841.00	1.03	866.23	1.27	1 068.08
Tank (kg)	415.65	1.20	498.76	1.33	551.42
Resin (kg)	112.51	1.20	135.01	1.33	149.27
Ceramic (kg)	221.42	1.20	265.70	1.33	293.75
Plastics (kg)	59.90	1.20	71.88	1.33	79.47
Powder coating/Paint (kg)	5.56	1.20	6.67	1.33	7.37
Total (kg)	5 224.87		6 269.58		6 931.57
Volume (m^3)	4.26	1.20	5.12	1.33	5.66
P_0 (W)	4 000.00		3 000.00		2 600.00
P_k (W)	18 000.00		18 000.00		16 000.00
Electricity losses (kWh/year)	62 415.00		53 655.00		47 109.33
Product price (€/unit)	28 191.74	1.14	32 138.58	1.31	36 931.18

Table 6-13: BC 6 improvement options constants

Load form factor (Kf)	1.5
Power factor (Pf)	0.9
Availability factor (Af)	1
Load factor (α)	0.25
Lifetime	25
Electricity rate (€/kWh)	0.3
Annual sales (m)	0.00232
EU stock (m)	0.016
Discount rate	4%
Landfill	4.2%

6.1.1.7 Improvement options for BC 7: Separation/isolation transformer 16 kVA

Table 6-14: BC 7 improvement options input data

	110-750	**110-400**	
		relative	**absolute**
Core Steel (kg)	50.00	1.10	55.00
Copper wire (kg)	35.00	1.57	54.95
Total (kg)	85.00		109.95
Volume of packaged final product (m^3)	0.04	1.29	0.05
P_0 (W)	110.00		110.00
P_k (W)	750.00		400.00
Electricity losses (kWh/year)	504.50		359.00
Product price (€/unit)	1 348.00	1.42	1 914.16

Table 6-15: BC 7 improvement options constants

Load form factor (Kf)	1.096
Power factor (Pf)	0.9
Availability factor (Af)	0.2
Load factor (α)	0.4
Lifetime	10
Electricity rate (€/kWh)	0.078
Annual sales (m)	0.075
EU stock (m)	0.75
Discount rate	4%
Landfill	1.0%

6.1.2 Option 2: Replace mineral oil with natural esters

Introduced in section 5.1.2.5, natural esters offer the advantage of biodegradability and improved environmental and health safety. With a flash point of 330°C, natural esters possess better fire safety characteristics than standard mineral oil, much greater than the flash point of 140°C for mineral oil.

Natural esters are refined from a variety of sources, but most often rapeseed in Europe. Rapeseed production oil involves seedbed preparation, sowing, fertilizing, crop protection with pesticides, rapeseed growth, harvesting, drying, storing, and crushing or extraction for refining[144]. A qualitative analysis is conducted in section 6.2.2.

6.2 Analysis BAT and LLCC

Scope: The design option(s) identified in the technical, environmental and economic analysis in subtask 6.1 should be ranked regarding the Best Available Technology (BAT) defined in subtask 5.1 and the Least (minimum) Life Cycle Costs:

- Ranking of the identified design options by LCC (e.g. option 1, option 2, option 3), considering possible trade-offs between different environmental impacts;
- Estimating the accumulative improvement and cost effect of implementing the ranked options simultaneously (e.g. option 1, option 1+2, option 1+2+3, etc.), also taking into account 'rebound' side effects of the individual design measures;
- Ranking of the accumulative design options, drawing of a LCC-curve (Y-axis= LLCC, X-axis=options) and identifying the Least Life Cycle Cost (LLCC) point and the BAT point[145]. The improvement potential resulting from the ranking should be discussed, such as the appropriateness to set minimum requirements at the LLCC point, to use the environmental performance of the BAT point or benchmarks set in other countries as benchmark or if manufacturers will make use of this ranking to evaluate alternative design solutions and the achieved environmental performance of the product.

6.2.1 Option 1: More material, higher grade steel, amorphous steel, and replacing aluminium with copper windings

All options are similar in that the improvement options assume increased material consumption that leads to improved energy performance. However, this creates variation in the reduction of environmental impacts for each base-case and its improvement options. This variation is due to two opposing factors: 1) Reduction of energy consumption leads to reduction of other environmental impacts, such as water, greenhouse gas emissions and acidification emissions; 2) Increase of embedded material in the transformer leads to higher environmental impacts, particularly with waste, polycyclic aromatic hydrocarbons (PAHs), particulate matter and eutrophication. The environmental impacts in which a medium option provides the greatest improvement means that a balance has been struck between reduction of energy and increase of materials.

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[144] Wetterholm, Cecilia. "Mineral and Vegetable Transformer Oils Equally Green?". Utility Automation and Engineering. 1 May 2008. http://www.elp.com/index/display/article-display/328725/articles/utility-automation-engineering-td/volume-13/issue-5/departments/news/mineral-and-vegetable-transformer-oils-equally-green.html Accessed 13 July 2010.

[145] This is usually the last point of the curve showing the product design with the lowest environmental impact, irrespective of the price.

6.2.1.1 Improvement options for BC 1: Distribution transformer 400 kVA

The results of the analysis of the improvement options for base-case 1 are seen below. As Table 6-16 shows, A0+Ak+ provides the greatest improvement in terms of energy consumption (-60%), which is only a slight improvement over other amorphous-based options. Option A0+Ck is the least life-cycle cost option (-27%). However, in many instances such as hazardous waste, particulate matter and eutrophication, the base-case achieves the least environmental impact, with option A0+Ak+ achieving the greatest impact.

Table 6-16: BC 1 Option 1 - Indicators

life-cycle indicators per unit	unit	D0Ck	C0Ck	B0Bk	A0Ck	A0Ak	A0+Ck*	A0+Bk*	A0+Ak*	A0+Ak+*
					Other resources and waste					
Total Energy (GER)	**GJ**	3 406.7	2 903.8	2 506.9	2 269.4	2 146.5	1 436.3	1 480.2	1 432.8	1 371.3
	% change with BC	0%	-15%	-26%	-33%	-37%	-58%	-57%	-58%	-60%
of which, electricity	**primary GJ**	3 314.9	2 801.8	2 384.8	2 143.1	1 987.7	1 281.0	1 293.5	1 226.7	1 121.6
	TWh	17.9	15.2	13.0	11.7	10.9	7.1	7.2	6.8	6.3
	% change with BC	0%	-15%	-28%	-35%	-39%	-61%	-60%	-62%	-65%
Water (process)	**kL**	223.0	189.0	161.7	145.7	135.9	88.7	90.3	86.1	80.1
	% change with BC	0%	-15%	-27%	-35%	-39%	-60%	-60%	-61%	-64%
Water (cooling)	**kL**	8 809.2	7 438.8	6 322.2	5 675.2	5 254.2	3 367.7	3 390.9	3 211.5	2 928.3
	% change with BC	0%	-16%	-28%	-36%	-40%	-62%	-62%	-64%	-67%
Waste, non-haz./ landfill	**kg**	8 355.1	8 094.7	9 040.7	8 648.8	11 015.7	8 382.3	9 932.7	11 547.1	18 835.5
	% change with BC	0%	-3%	8%	4%	32%	0%	19%	38%	125%
Waste, hazardous/ incinerated	**kg**	343.8	359.1	399.8	412.2	485.8	465.6	557.7	586.1	689.4
	% change with BC	0%	4%	16%	20%	41%	35%	62%	71%	101%
					Emissions (Air)					
Greenhouse Gases in GWP100	**t CO2 eq.**	149.0	127.1	109.8	99.5	94.2	63.2	65.2	63.3	60.7
	% change with BC	0%	-15%	-26%	-33%	-37%	-58%	-56%	-58%	-59%
Ozone Depletion, emissions	**mg R-11 eq.**	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	% change with BC	0%	0%	0%	0%	0%	0%	0%	0%	0%
Acidification, emissions	**kg SO2 eq.**	911.7	783.7	696.4	631.6	627.8	418.7	441.7	451.7	536.7
	% change with BC	0%	-14%	-24%	-31%	-31%	-54%	-52%	-50%	-41%
Volatile Organic Compounds (VOC)	**kg**	1.8	1.6	1.5	1.5	1.6	1.3	1.5	1.5	1.6
	% change with BC	0%	-8%	-12%	-15%	-11%	-26%	-16%	-15%	-8%
Persistent Organic Pollutants (POP)	**mg i-Teq**	38.8	37.4	37.0	37.2	39.2	35.9	41.9	41.1	42.2

life-cycle indicators per unit	unit	D0Ck	C0Ck	B0Bk	A0Ck	A0Ak	A0+Ck*	A0+Bk*	A0+Ak*	A0+Ak+*
	% change with BC	0%	-4%	-5%	-4%	1%	-7%	8%	6%	9%
Heavy Metals	**g Ni eq.**	75.3	68.0	66.0	61.8	68.1	50.3	56.7	60.7	82.6
	% change with BC	0%	-10%	-12%	-18%	-10%	-33%	-25%	-19%	10%
PAHs	**g Ni eq.**	14.3	13.9	15.1	14.7	17.9	19.5	21.9	26.1	17.8
	% change with BC	0%	-3%	6%	3%	25%	36%	53%	82%	24%
Particulate Matter (PM, dust)	**kg**	56.8	57.5	61.7	62.7	71.8	68.0	79.8	83.6	94.4
	% change with BC	0%	1%	9%	10%	26%	20%	40%	47%	66%
Emissions (Water)										
Heavy Metals	**g Hg/20**	28.5	25.8	25.0	23.5	25.7	21.2	23.7	25.0	23.1
	% change with BC	0%	-9%	-12%	-17%	-10%	-26%	-17%	-12%	-19%
Eutrophication	**kg PO4**	0.4	0.4	0.5	0.5	0.6	0.5	0.6	0.7	0.8
	% change with BC	0%	20%	33%	37%	62%	52%	82%	92%	135%
Persistent Organic Pollutants (POP)	**ng i-Teq**	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	% change with BC	0%	0%	0%	0%	0%	0%	0%	0%	0%
Economic indicators										
Electricity cost	**€**	12 132.58	10 239.22	8 697.67	7 804.90	7 221.00	4 620.38	4 647.71	4 399.44	4 005.94
	% change with BC	0%	-16%	-28%	-36%	-40%	-62%	-62%	-64%	-67%
Life-cycle cost	**€**	18 254.63	16 667.37	15 982.91	14 906.48	15 914.31	13 252.48	14 687.87	15 113.03	16 923.47
	% change with BC	0%	-9%	-12%	-18%	-13%	-27%	-20%	-17%	-7%

* amorphous steel core

Figure 6-1 below displays total energy, with total electricity consumption as a percentage of total energy consumption. As the results clearly show, electricity consumption and thus the use phase dominates energy consumption, representing greater than 93% for all silicon steel-based options, while over 82% for amorphous steel-based options.

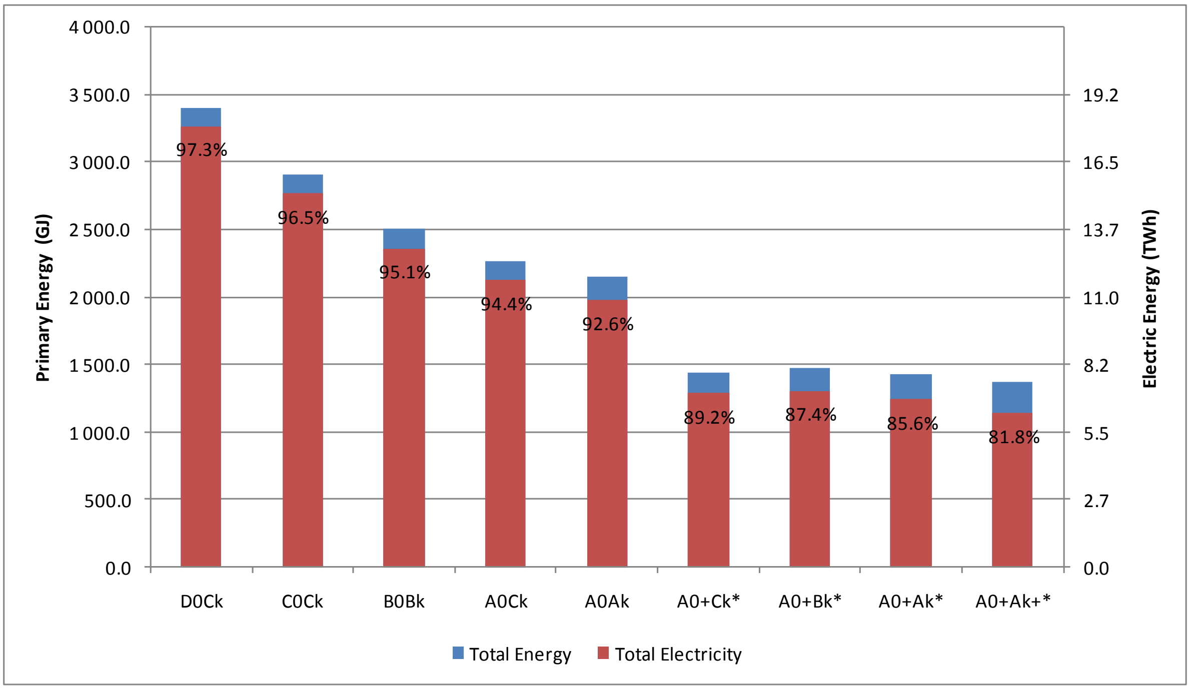

Figure 6-1: BC 1 Option 1 - Total energy and electricity consumption

Figure 6-2 shows product prices as a percentage of life-cycle costs. The part in blue represents electricity costs over the lifetime of the transformer. Product price represents 33-55% of life-cycle cost for these options. As the figure shows, A0Ck achieves least life-cycle cost of € 13 252.

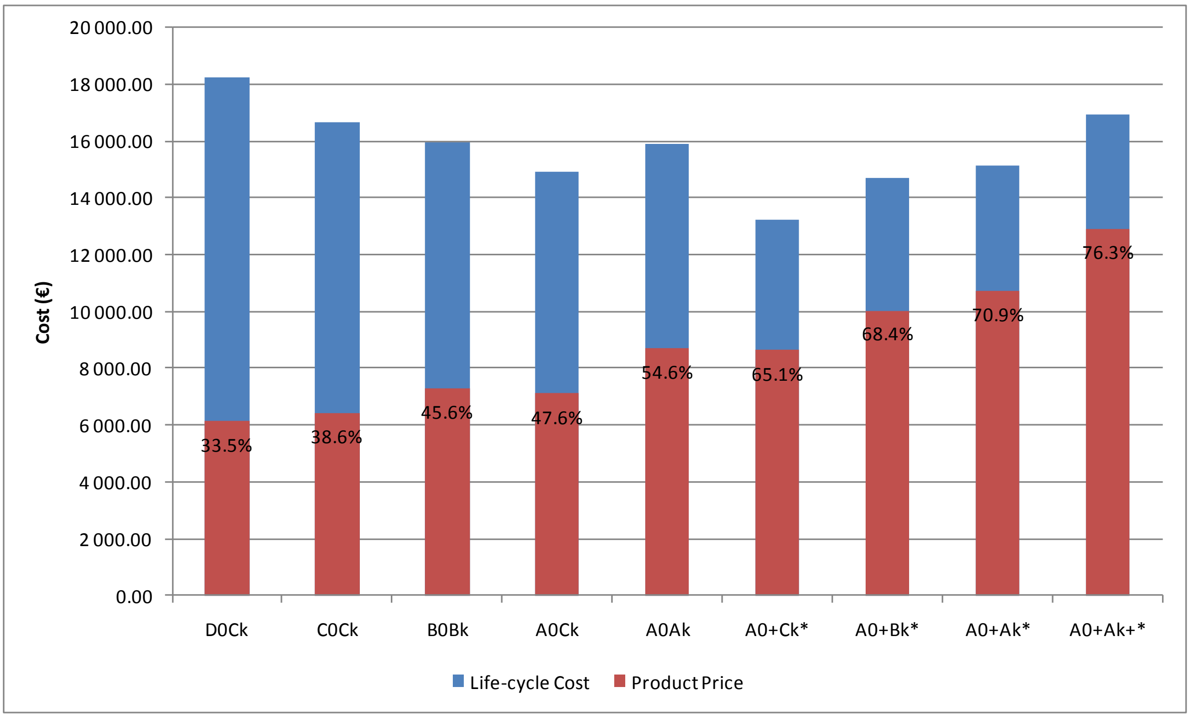

Figure 6-2: BC 1 Option 1 - Life-cycle cost and product price

Figure 6-3 compares total energy consumption with life-cycle cost in order to obtain a picture of how cost relates to general environmental performance. As the figure shows, the least life-cycle cost of A0+Ck does not match the lowest energy consumption of A0+Ak+. However, the energy consumption of A0+Ck is only 5% greater than that of A0+Ak+.

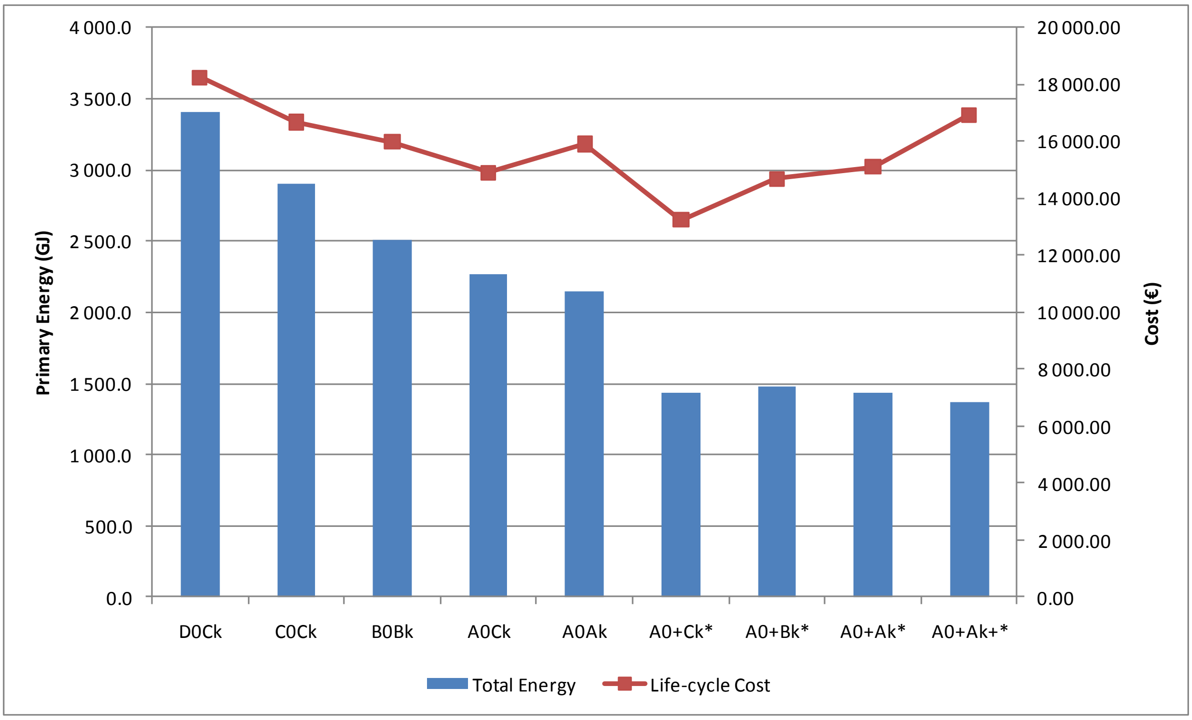

Figure 6-3: BC 1 Option 1 - Total energy consumption and life-cycle cost

Focus on the different environmental impact categories

Even if the implementation of improvement options reduces many environmental impacts in comparison with the base-case, it is not the case for all of them. This section discusses the relative importance of each impact category for which the improvement options do not lower the environmental impacts.

- Generation of hazardous and non-hazardous waste: this impact category is only a quantification of the waste generated and is directly related to the quantity of material that is contained in the product. However, the major environmental impacts that are due to this waste management (e.g. incineration) are also accounted for in other emissions impact categories. Thus, this category gives an interesting indicator but should be considered as a priority. This point of view was supported by the JRC during a discussion on the incineration of mineral oil.

- Eutrophication: in order to compare the relative importance of the different impact categories, we used the normalisation weighting set (World 1995[146]) of the CML method. The results are presented in Table 6-17. When normalised, the eutrophication value is around 500 times lower than the acidification and Global Warming Potential (GWP) values. Thus, this impact category should be considered less important for the specific case of transformers, in comparison with other impact categories such as GWP and Acidification.

Table 6-17: Normalisation of some impact categories for base case 1 option 1 results

Impact Category	Impacts of Base Case 1 Option 1 A0+Ak+	Normalised impacts
Acidification	536.7 kg SO_2 eq	1.67E-09
Global Warming Potential	60.7 t CO_2 eq	1.46E-09
Eutrophication	0.8 kg PO_4	6.33E-12

- PAHs and Particulate Matter: the normalisation was not possible in that case as these emissions are not standard impacts found in Life Cycle Assessment methods. However, these are emission indicators and are related to ecotoxicity. Given the function and composition of a transformer, it seems relevant to consider that its emissions to the environment will be rather low: no direct emissions occur during the use phase, which is very long and results in a very high amount of electricity lost. Thus, it seems reasonable to consider that these impact categories should not be considered as a priority.

6.2.1.2 Improvement options for BC 2: Oil-immersed industry transformer 1 MVA

The results of the analysis of the improvement options for base-case 2 are seen below. As Table 6-18 shows, A0+Ak+ provides the greatest improvement in terms of energy consumption (-54%), while option A0Ak is the least life-cycle cost (-19%) option. However, in many instances such as hazardous waste, particulate matter and

146 Normalisation factors specified in this method: Acidification 3.11 E-12 kg^{-1} SO_2 eq; Global Warming Potential 2.41 E-14 kg^{-1} CO_2 eq; Eutrophication 7.56 E-12 kg^{-1} PO_4 eq.

eutrophication, the base-case achieves the least environmental impact, with option A0+Ak+ achieving the greatest impact.

Table 6-18: BC 2 Option 1 - Indicators

life-cycle indicators per unit	unit	E0Ck	C0Ck	B0Bk	A0Ck	A0Ak	A0+Ck*	A0+Bk*	A0+Ak*	A0+Ak+*
					Other resources and waste					
Total Energy (GER)	**GJ**	7 344.6	5 996.4	5 219.8	5 288.1	4 486.7	4 574.7	4 177.2	3 833.7	3 377.3
	% change with BC	0%	-18%	-29%	-28%	-39%	-38%	-43%	-48%	-54%
of which, electricity	**primary GJ**	7 158.3	5 782.5	4 958.3	5 028.5	4 146.8	4 236.5	3 794.7	3 406.1	2 844.9
	TWh	13.8	11.2	9.6	9.7	8.1	8.2	7.4	6.7	5.6
	% change with BC	0%	-19%	-30%	-29%	-42%	-40%	-46%	-52%	-59%
Water (process)	**kL**	480.6	389.4	335.2	339.9	282.5	288.4	259.7	234.5	199.1
	% change with BC	0%	-19%	-30%	-29%	-41%	-40%	-46%	-51%	-59%
Water (cooling)	**kL**	19 033.0	15 355.9	13 149.8	13 335.3	10 966.9	11 197.3	10 007.2	8 964.1	7 460.3
	% change with BC	0%	-19%	-31%	-30%	-42%	-41%	-47%	-53%	-61%
Waste, non-haz./ landfill	**kg**	18 092.6	18 024.9	20 885.4	20 380.4	25 171.3	21 366.0	23 045.1	25 901.4	43 998.6
	% change with BC	0%	0%	15%	13%	39%	18%	27%	43%	143%
Waste, hazardous/ incinerated	**kg**	658.7	699.3	779.6	786.6	947.6	971.6	1 069.2	1 142.8	1 366.8
	% change with BC	0%	6%	18%	19%	44%	48%	62%	73%	108%
					Emissions (Air)					
Greenhouse Gases in GWP100	**t CO2 eq.**	321.2	262.4	228.8	231.7	197.1	200.9	183.8	169.0	149.3
	% change with BC	0%	-18%	-29%	-28%	-39%	-37%	-43%	-47%	-54%
Ozone Depletion, emissions	**mg R-11 eq.**	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	% change with BC	0%	0%	0%	0%	0%	0%	0%	0%	0%
Acidification, emissions	**kg SO2 eq.**	1 976.7	1 643.5	1 488.4	1 496.5	1 354.9	1 315.4	1 232.3	1 182.9	1 320.7
	% change with BC	0%	-17%	-25%	-24%	-31%	-33%	-38%	-40%	-33%
Volatile Organic Compounds (VOC)	**kg**	3.6	3.2	3.1	3.1	3.1	3.2	3.2	3.2	3.4
	% change with BC	0%	-11%	-15%	-14%	-14%	-11%	-11%	-11%	-7%
Persistent Organic Pollutants (POP)	**mg i-Teq**	79.8	75.5	74.1	75.9	79.0	85.2	88.8	88.7	90.0

life-cycle indicators per unit	unit	E0Ck	C0Ck	B0Bk	A0Ck	A0Ak	A0+Ck*	A0+Bk*	A0+Ak*	A0+Ak+*
	% change with BC	0%	-5%	-7%	-5%	-1%	7%	11%	11%	13%
Heavy Metals	**g Ni eq.**	159.6	141.6	140.0	139.7	144.1	134.5	134.9	138.8	188.8
	% change with BC	0%	-11%	-12%	-13%	-10%	-16%	-15%	-13%	18%
PAHs	**g Ni eq.**	30.3	30.1	33.9	33.4	40.2	46.6	52.0	59.6	36.0
	% change with BC	0%	-1%	12%	10%	32%	54%	72%	96%	19%
Particulate Matter (PM, dust)	**kg**	105.4	106.8	114.9	115.9	133.9	138.3	149.7	158.6	179.7
	% change with BC	0%	1%	9%	10%	27%	31%	42%	50%	71%
					Emissions (Water)					
Heavy Metals	**g Hg/20**	57.7	50.6	48.4	48.7	48.3	50.9	51.5	52.8	45.9
	% change with BC	0%	-12%	-16%	-16%	-16%	-12%	-11%	-8%	-20%
Eutrophication	**kg PO4**	0.7	0.8	0.8	0.8	1.0	1.0	1.1	1.2	1.5
	% change with BC	0%	4%	16%	17%	40%	40%	53%	63%	107%
Persistent Organic Pollutants (POP)	**ng i-Teq**	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	% change with BC	0%	0%	0%	0%	0%	0%	0%	0%	0%
					Economic indicators					
Electricity cost	**€**	33 105.33	26 700.78	22 855.89	23 178.28	19 046.72	19 444.82	17 367.32	15 547.97	12 923.78
	% change with BC	0%	-19%	-31%	-30%	-42%	-41%	-48%	-53%	-61%
Life-cycle cost	**€**	44 031.33	38 828.64	36 622.65	36 726.52	35 763.50	38 346.80	38 235.98	38 055.53	41 549.90
	% change with BC	0%	-12%	-17%	-17%	-19%	-13%	-13%	-14%	-6%

*amorphous steel core

Figure 6-4 below displays total energy, with total electricity consumption as a percentage of total energy consumption. As the results clearly show, electricity consumption and thus the use phase dominates energy consumption, representing greater than 93% for all silicon steel-based options, and over 84% for all amorphous steel-based options.

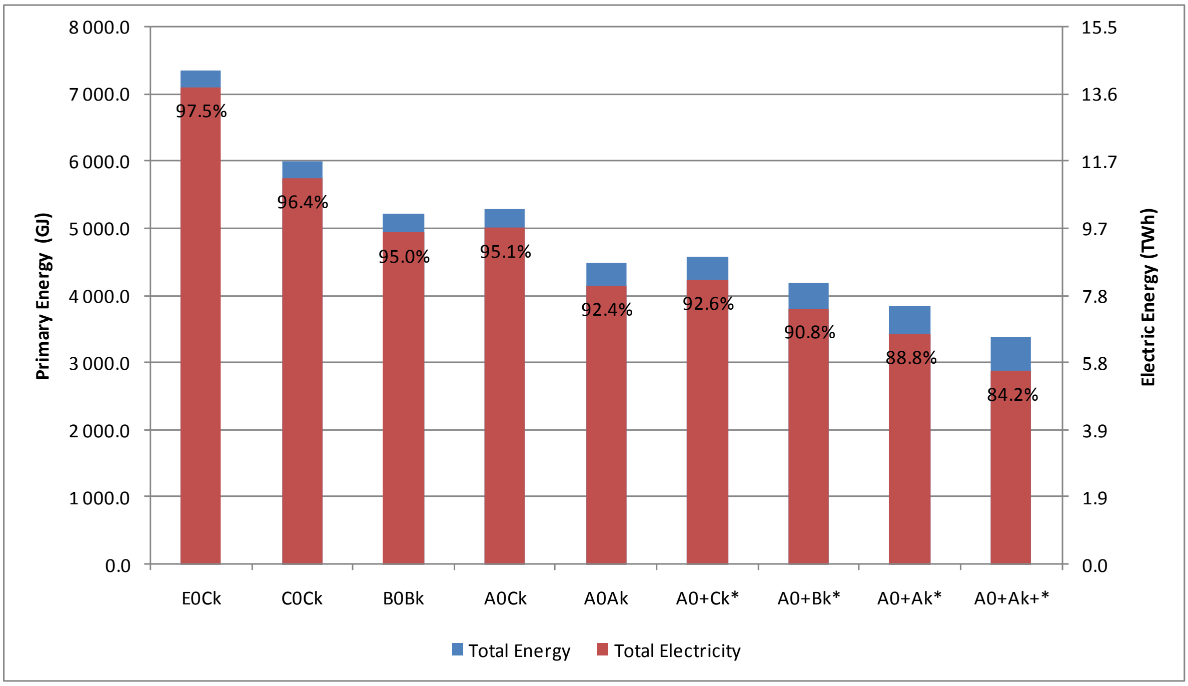

Figure 6-4: BC 2 Option 1 - Total energy and electricity consumption

Figure 6-5 shows product prices as a percentage of life-cycle costs. The part in blue represents electricity costs over the lifetime of the transformer. Product price represents 25-69% of life-cycle cost for these options. As the figure shows, A0Ak achieves least life-cycle cost of € 35 764.

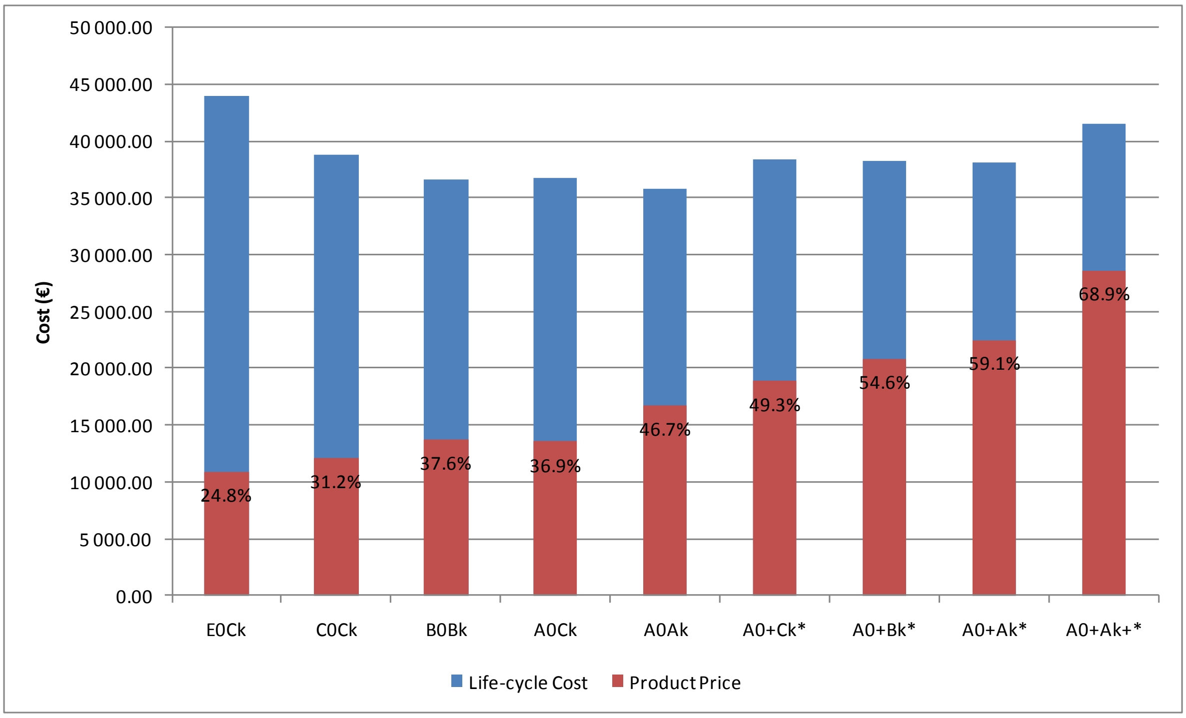

Figure 6-5: BC 2 Option 1 - Life-cycle cost and product price

Figure 6-6 compares total energy consumption with life-cycle cost in order to obtain a picture of how cost relates to general environmental performance. As the figure shows, the least life-cycle cost of A0Ak does not match the lowest energy consumption of option A0+Ak+.

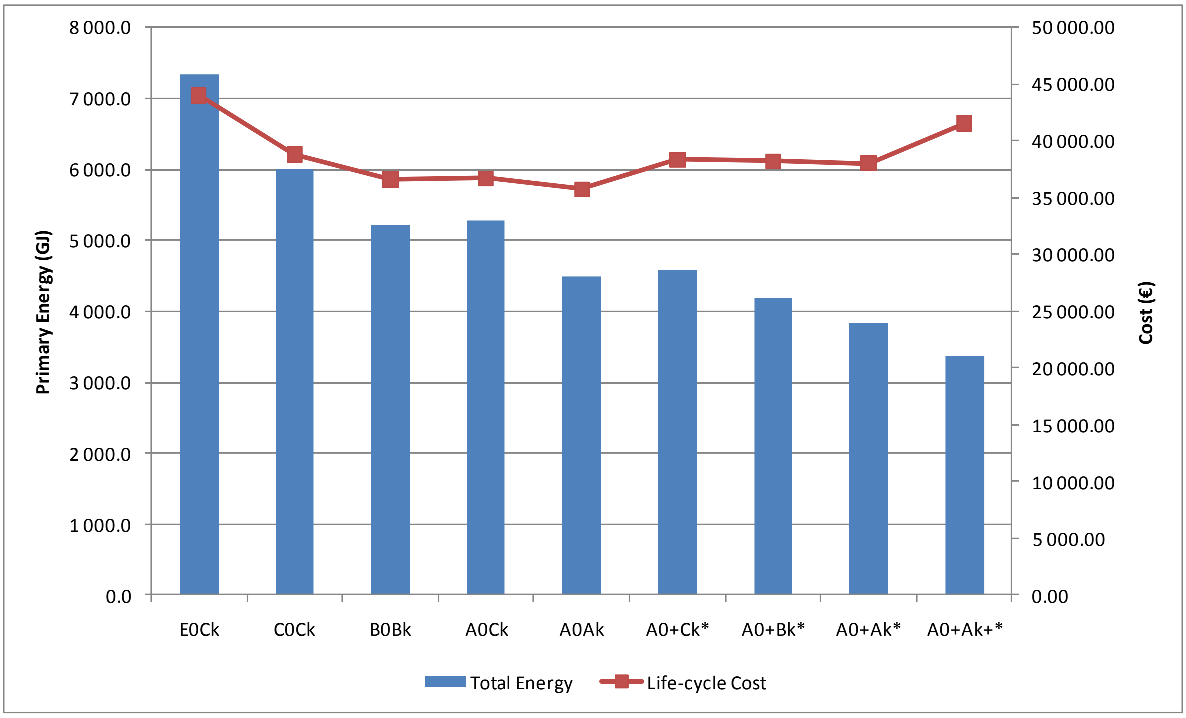

Figure 6-6: BC 2 Option 1 - Total energy consumption and life-cycle cost

6.2.1.3 Improvement options for BC 3: Dry-type industry transformer 1.25 MVA

The results of the analysis of the improvement options for base-case 3 are seen below. As Table 6-19 shows, A0+Ak provides the greatest improvement in terms of energy consumption (-50%), while A0Bk is the least life-cycle cost (-13%) option. However, in certain instances such as PAHs and eutrophication, the base-case achieves the least environmental impact, with option A0Ak often achieving the greatest impact.

Table 6-19: BC 3 Option 1 - Indicators

life-cycle indicators per unit	unit	C0Bk	B0Bk	A0Bk	A0Ak	A0+Ak*
		Other resources and waste				
Total Energy (GER)	GJ	13 144.4	11 271.9	10 516.2	9 893.4	6 564.6
	% change with BC	0%	-14%	-20%	-25%	-50%
of which, electricity	primary GJ	12 640.4	10 721.4	9 908.2	9 192.5	5 874.5
	TWh	4.4	3.8	3.5	3.2	2.1
	% change with BC	0%	-15%	-21%	-26%	-52%
Water (process)	kL	847.7	720.2	666.6	619.7	397.0
	% change with BC	0%	-15%	-21%	-27%	-53%
Water (cooling)	kL	33 554.7	28 421.8	26 235.7	24 302.1	15 423.9
	% change with BC	0%	-15%	-22%	-28%	-54%
Waste, non-haz./ landfill	kg	22 199.0	20 583.2	20 472.0	21 321.1	28 140.4
	% change with BC	0%	-7%	-8%	-4%	27%

life-cycle indicators per unit	unit	C0Bk	B0Bk	A0Bk	A0Ak	A0+Ak*
Waste, hazardous/ incinerated	kg	3 128.2	3 362.5	3 673.0	4 131.7	4 083.3
	% change with BC	0%	7%	17%	32%	31%
			Emissions (Air)			
Greenhouse Gases in GWP100	t CO2 eq.	574.3	492.6	459.6	432.7	286.8
	% change with BC	0%	-14%	-20%	-25%	-50%
Ozone Depletion, emissions	mg R-11 eq.	0.0	0.0	0.0	0.0	0.0
	% change with BC	0%	0%	0%	0%	0%
Acidification, emissions	kg SO2 eq.	3 368.8	2 883.3	2 686.2	2 529.1	1 826.2
	% change with BC	0%	-14%	-20%	-25%	-46%
Volatile Organic Compounds (VOC)	kg	5.8	5.2	5.0	4.9	3.7
	% change with BC	0%	-11%	-14%	-16%	-37%
Persistent Organic Pollutants (POP)	mg i-Teq	137.2	130.4	131.6	134.5	116.0
	% change with BC	0%	-5%	-4%	-2%	-15%
Heavy Metals	g Ni eq.	285.4	258.9	252.8	252.8	230.1
	% change with BC	0%	-9%	-11%	-11%	-19%
PAHs	g Ni eq.	61.5	59.6	61.6	71.6	17.7
	% change with BC	0%	-3%	0%	17%	-71%
Particulate Matter (PM, dust)	kg	354.9	371.7	399.7	443.6	420.5
	% change with BC	0%	5%	13%	25%	18%
			Emissions (Water)			
Heavy Metals	g Hg/20	117.6	108.2	106.9	110.1	75.0
	% change with BC	0%	-8%	-9%	-6%	-36%
Eutrophication	kg PO4	3.1	3.3	3.6	4.0	2.9
	% change with BC	0%	7%	16%	30%	-5%
Persistent Organic Pollutants (POP)	ng i-Teq	0.0	0.0	0.0	0.0	0.0
	% change with BC	0%	0%	0%	0%	0%
			Economic indicators			
Electricity cost	€	53 583.45	45 312.74	41 768.15	38 614.21	24 424.35
	% change with BC	0%	-15%	-22%	-28%	-54%
Life-cycle cost	€	69 916.52	62 789.12	60 551.18	63 113.81	65 093.70
	% change with BC	0%	-10%	-13%	-10%	-7%

* amorphous steel core

Figure 6-7 below displays total energy, with total electricity consumption as a percentage of total energy consumption. As the results clearly show, electricity consumption and thus the use phase dominates energy consumption, representing greater than 89% for all options.

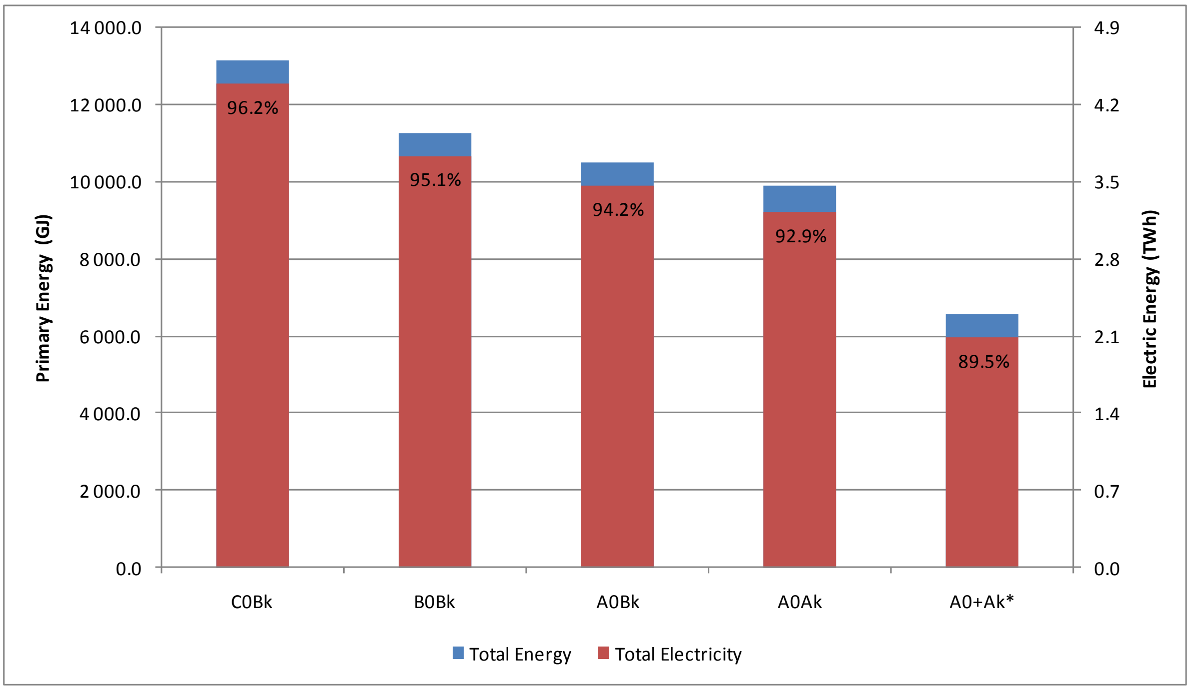

Figure 6-7: BC 3 Option 1 - Total energy and electricity consumption

Figure 6-8 shows product prices as a percentage of life-cycle costs. The part in blue represents electricity costs over the lifetime of the transformer. Product price represents 24-63% of life-cycle cost for these options. As the figure shows, A0Bk achieves least life-cycle cost of € 60 551.

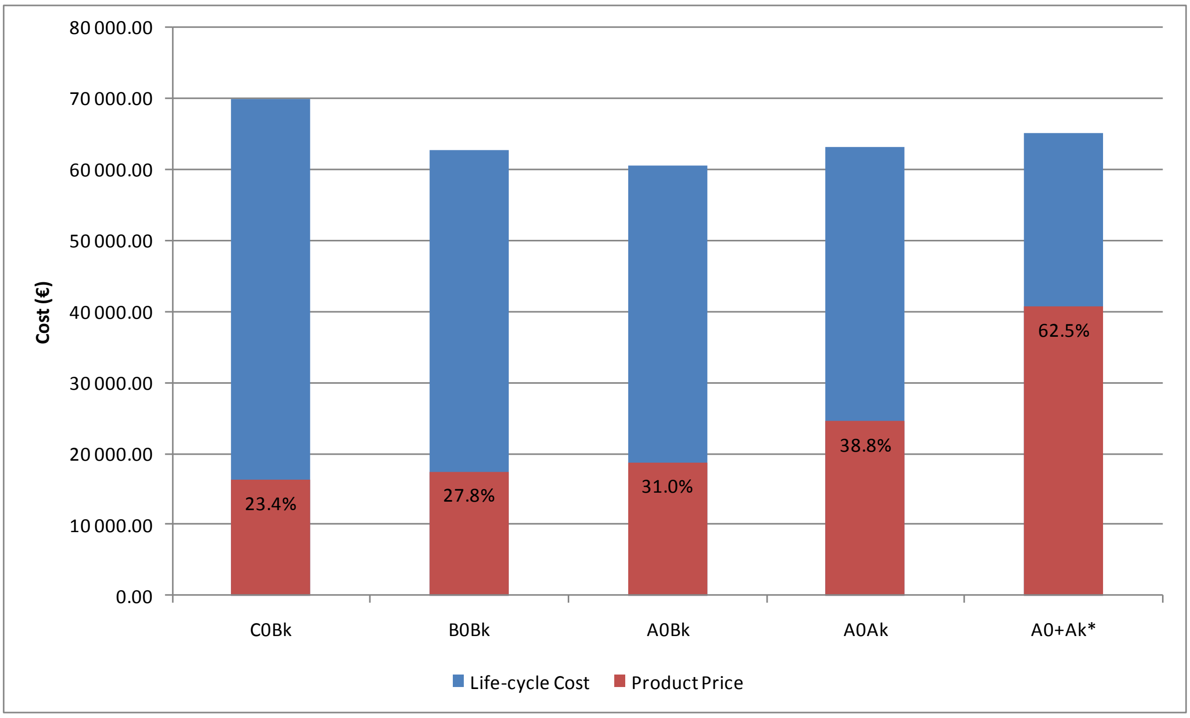

Figure 6-8: BC 3 Option 1 - Life-cycle cost and product price

Figure 6-9 compares total energy consumption with life-cycle cost in order to obtain a picture of how cost relates to general environmental performance. As the figure shows, the least life-cycle cost of A0Bk does not match the lowest energy consumption option of A0+Ak. Option A0Bk consumes 60% more primary energy than A0+Ak over its lifetime.

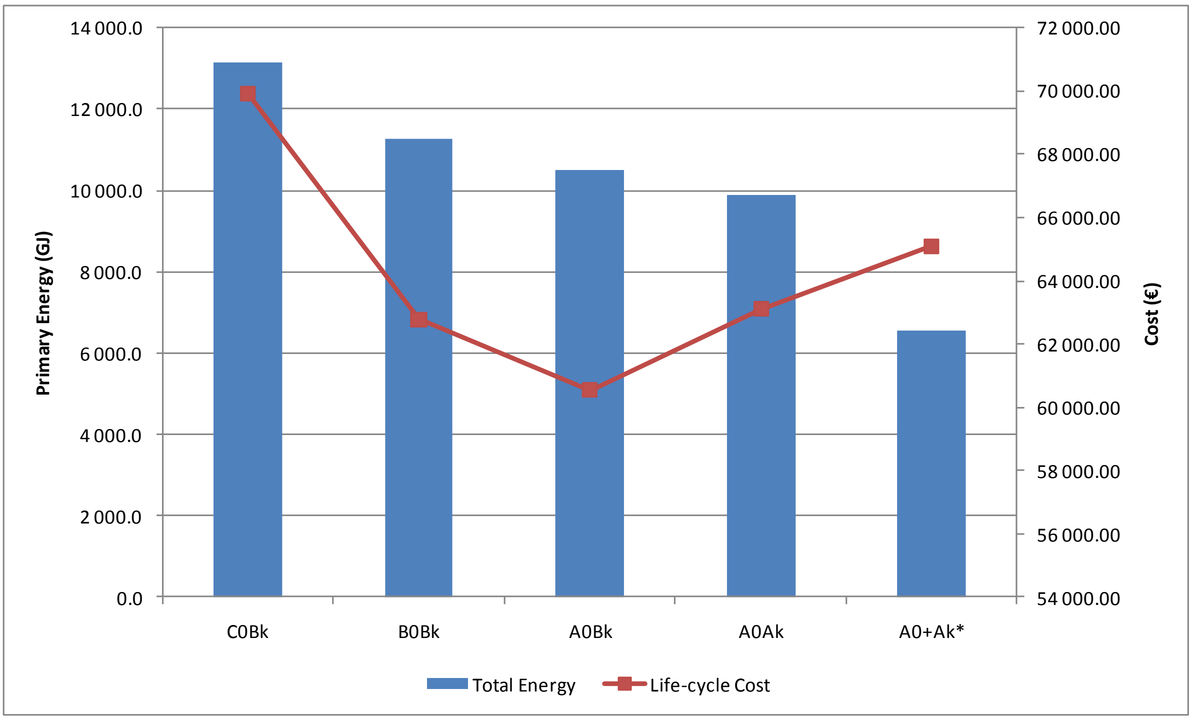

Figure 6-9: BC 3 Option 1 - Total energy consumption and life-cycle cost

6.2.1.4 Improvement options for BC 4: Power transformer 100 MVA

The results of the analysis of the improvement options for base-case 4 are seen below. As Table 6-20 shows, 20-228 provides the greatest improvement in terms of energy consumption (-37%), while 34-326 is the least life-cycle cost (-2%) option. However, in many instances such as waste, VOC, heavy metals, PAHs, particulate matter and eutrophication, option 20-228 achieves the greatest impact.

Table 6-20: BC 4 Option 1 - Indicators

life-cycle indicators per unit	unit	41-326	34-326	34-277	34-228	28-326	28-277	28-228	20-326	20-277	20-228
Other resources and waste											
Total Energy (GER)	**GJ**	172 912.7	156 335.5	149 581.9	143 354.0	139 572.1	132 975.3	127 192.7	118 836.2	112 854.4	109 549.5
	% change with BC	0%	-10%	-13%	-17%	-19%	-23%	-26%	-31%	-35%	-37%
of which, electricity	**primary GJ**	164 808.2	148 014.6	140 347.4	132 685.0	131 251.3	123 582.4	115 931.5	108 917.0	101 277.2	93 804.8
	TWh	33.9	30.5	28.9	27.3	27.0	25.5	23.9	22.4	20.9	19.4
	% change with BC	0%	-10%	-15%	-19%	-20%	-25%	-30%	-34%	-38%	-43%
Water (process)	**kL**	11 124.6	10 006.9	9 510.2	9 020.5	8 889.3	8 394.5	7 911.3	7 420.8	6 936.0	6 498.6
	% change with BC	0%	-10%	-15%	-19%	-20%	-25%	-29%	-33%	-38%	-42%
Water (cooling)	**kL**	437 018.2	392 305.1	732 244.7	351 018.9	347 602.9	326 955.3	306 335.3	288 045.3	267 426.3	246 952.0
	% change with BC	0%	-10%	68%	-20%	-20%	-25%	-30%	-34%	-39%	-43%
Waste, non-haz./ landfill	**kg**	639 817.5	669 995.6	732 244.7	867 861.4	650 559.5	736 993.0	929 168.1	848 435.4	1 003 304.0	1 425 734.9
	% change with BC	0%	5%	14%	36%	2%	15%	45%	33%	57%	123%
Waste, hazardous/ incinerated	**kg**	30 641.9	30 276.1	32 746.6	36 120.8	29 889.9	32 600.8	36 811.1	32 172.3	36 161.0	46 094.9
	% change with BC	0%	-1%	7%	18%	-2%	6%	20%	5%	18%	50%
Emissions (Air)											
Greenhouse Gases in GWP100	**t CO2 eq.**	7 564.3	6 842.7	6 550.8	6 284.6	6 111.2	5 827.0	5 582.4	5 214.7	4 960.0	4 832.3
	% change with BC	0%	-10%	-13%	-17%	-19%	-23%	-26%	-31%	-34%	-36%
Ozone Depletion, emissions	**mg R-11 eq.**	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	% change with BC	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Acidification, emissions	**kg SO2 eq.**	48 695.0	45 164.6	44 237.6	44 454.9	40 848.0	40 299.4	41 395.9	38 582.0	39 091.7	43 719.1
	% change with BC	0%	-7%	-9%	-9%	-16%	-17%	-15%	-21%	-20%	-10%
Volatile Organic Compounds (VOC)	**kg**	111.0	104.4	106.1	109.2	98.0	100.1	104.4	93.6	97.7	111.6
	% change with BC	0%	-6%	-4%	-2%	-12%	-10%	-6%	-16%	-12%	1%
Persistent Organic Pollutants	**mg i-Teq**	2 364.1	2 192.7	2 235.1	2 247.1	2 082.9	2 111.2	2 109.5	1 846.5	1 876.7	1 979.7

life-cycle indicators per unit	unit	41-326	34-326	34-277	34-228	28-326	28-277	28-228	20-326	20-277	20-228
(POP)	% change with BC	0%	-7%	-5%	-5%	-12%	-11%	-11%	-22%	-21%	-16%
Heavy Metals	g Ni eq.	4 609.7	4 465.1	4 586.8	4 936.5	4 177.5	4 373.3	4 901.4	4 490.3	4 907.0	6 205.3
	% change with BC	0%	-3%	0%	7%	-9%	-5%	6%	-3%	6%	35%
PAHs	g Ni eq.	980.9	963.7	1 021.7	1 119.9	930.7	1 000.8	1 132.7	1 010.2	1 126.2	1 440.1
	% change with BC	0%	-2%	4%	14%	-5%	2%	15%	3%	15%	47%
Particulate Matter (PM, dust)	kg	4 168.0	4 077.1	4 355.5	4 742.3	3 984.9	4 292.0	4 779.3	4 197.5	4 658.7	5 838.0
	% change with BC	0%	-2%	4%	14%	-4%	3%	15%	1%	12%	40%
Emissions (Water)											
Heavy Metals	g Hg/20	1 532.7	1 438.9	1 443.4	1 480.5	1 330.8	1 345.3	1 409.2	1 286.2	1 336.6	1 540.1
	% change with BC	0%	-6%	-6%	-3%	-13%	-12%	-8%	-16%	-13%	0%
Eutrophication	kg PO4	27.4	27.1	29.2	32.3	26.6	29.0	33.0	29.1	32.7	42.1
	% change with BC	0%	-1%	7%	18%	-3%	6%	20%	6%	19%	54%
Persistent Organic Pollutants (POP)	ng i-Teq	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	% change with BC	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Economic indicators											
Electricity cost	€	700 382.66	628 604.71	595 325.26	562 045.81	556 826.76	523 547.31	490 267.86	461 122.82	427 843.37	394 563.93
	% change with BC	0%	-10%	-15%	-20%	-20%	-25%	-30%	-34%	-39%	-44%
Life-cycle cost	€	1 456 225.66	1 429 798.29	1 502 336.86	1 771 394.61	1 456 279.93	1 574 169.08	2 001 953.86	1 821 640.22	2 052 905.82	2 284 171.43
	% change with BC	0%	-2%	3%	22%	0%	8%	37%	25%	41%	57%

Figure 6-10 below displays total energy, with total electricity consumption as a percentage of total energy consumption. As the results clearly show, electricity consumption and thus the use phase dominates energy consumption, representing greater than 86% for all options.

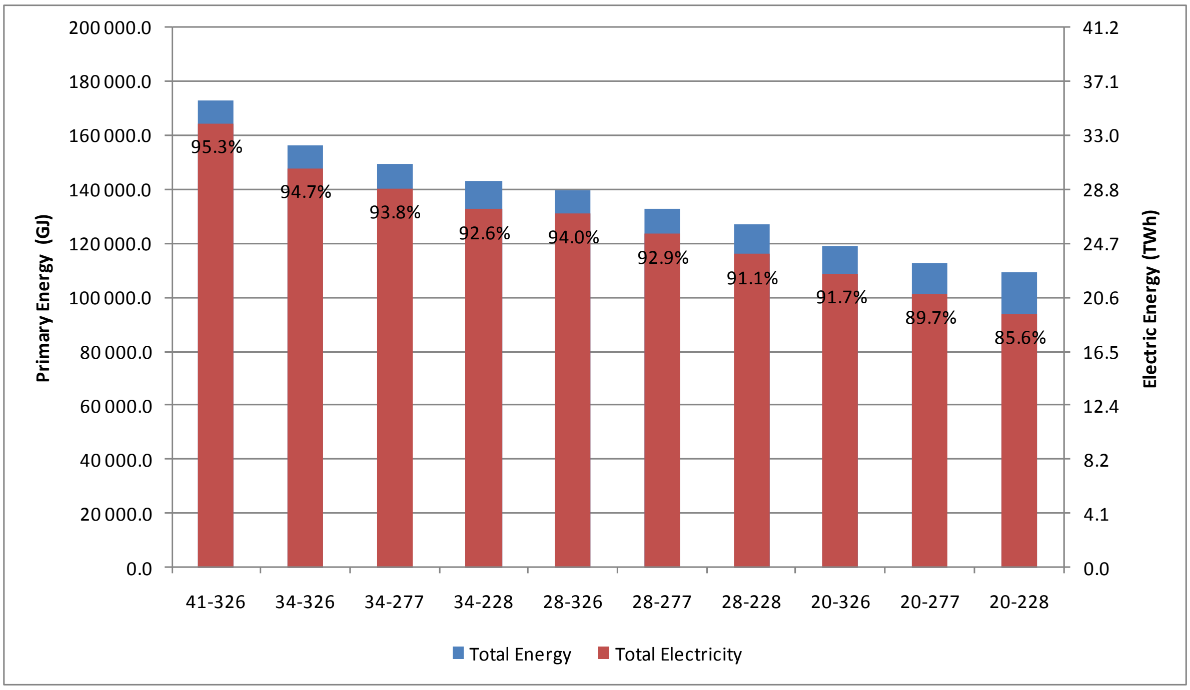

Figure 6-10: BC 4 Option 1 - Total energy and electricity consumption

Figure 6-11 shows product prices as a percentage of life-cycle costs. The part in blue represents electricity costs over the lifetime of the transformer. Product price represents 52-83% of life-cycle cost for these options. As the figure shows, 34-326 achieves least life-cycle cost of € 1 429 798.

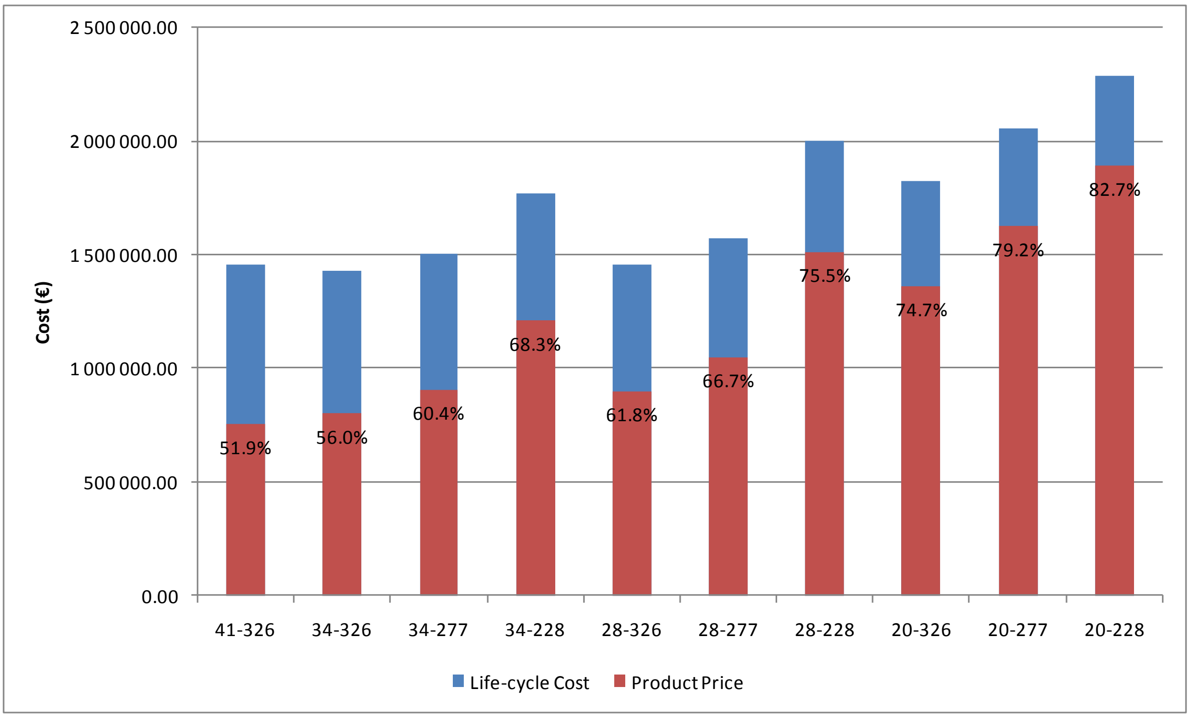

Figure 6-11: BC 4 Option 1 - Life-cycle cost and product price

Figure 6-12 compares total energy consumption with life-cycle cost in order to obtain a picture of how cost relates to general environmental performance. As the figure shows, the least life-cycle cost of 34-326 does not match the lowest energy consumption option of 20-228. Option 34-326 consumes 43% more primary energy than 20-228 over its lifetime.

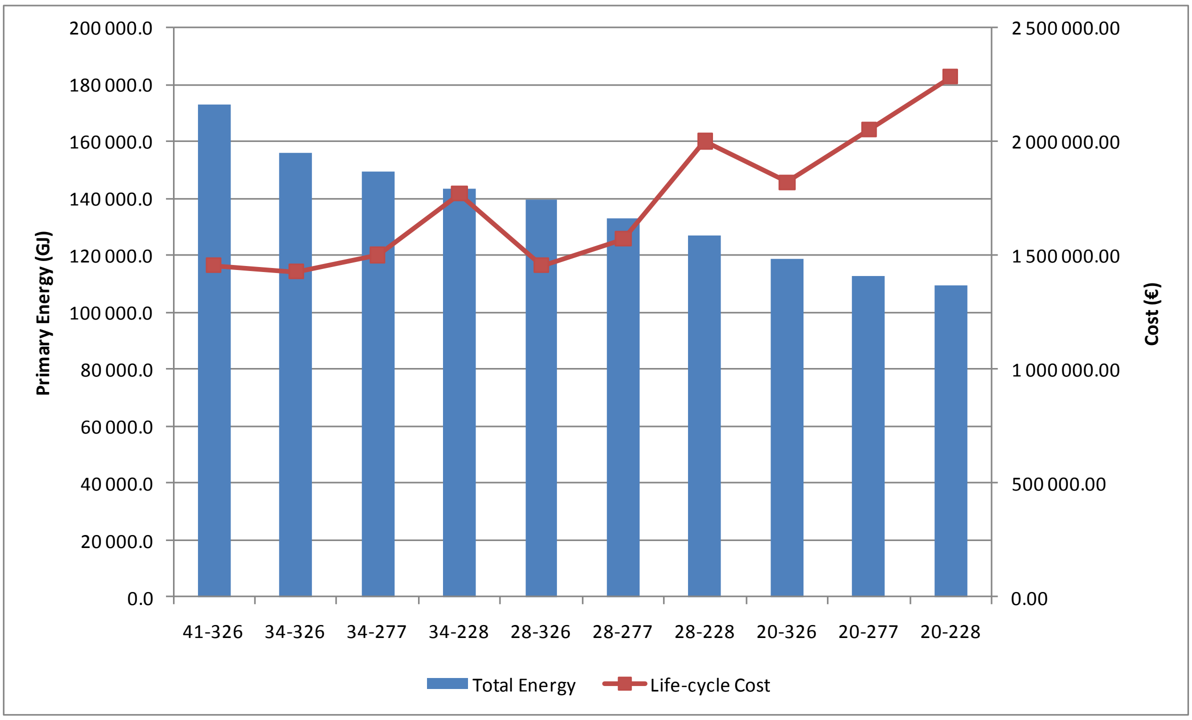

Figure 6-12: BC 4 Option 1 - Total energy consumption and life-cycle cost

6.2.1.5 Improvement options for BC 5: DER transformer oil-immersed 2 MVA

The results of the analysis of the improvement options for base-case 5 are seen below. As Table 6-21 shows, A0+Ak provides the greatest improvement in terms of energy consumption (-56%), as well as attaining least life-cycle cost (-49%). However, in certain instances such as waste, PAHs, particulate matter and eutrophication, the base-case achieves the least environmental impact, with option A0+Ak achieving the greatest impact.

Table 6-21: BC 5 Option 1 - Indicators

life-cycle indicators per unit	unit	E0Ck	C0Ck	A0Ak	A0+Ck*	A0+Bk*	A0+Ak*
			Other resources and waste				
Total Energy (GER)	**GJ**	15 912.5	13 646.0	9 982.5	10 841.6	8 693.4	7 055.8
	% change with BC	0%	-14%	-37%	-32%	-45%	-56%
of which, electricity	**primary GJ**	15 564.0	13 268.3	9 398.1	10 311.9	8 080.4	6 249.6
	TWh	0.2	0.2	0.1	0.2	0.1	0.1
	% change with BC	0%	-15%	-39%	-33%	-47%	-58%
Water (process)	**kL**	1 044.7	892.3	637.9	699.0	551.7	433.7
	% change with BC	0%	-15%	-39%	-33%	-47%	-58%
Water (cooling)	**kL**	41 414.7	35 286.5	24 934.8	27 340.5	21 376.5	16 475.7
	% change with BC	0%	-15%	-40%	-34%	-48%	-60%
Waste, non-haz./ landfill	**kg**	35 724.5	34 819.6	46 095.5	35 321.3	38 570.2	60 760.5
	% change with BC	0%	-3%	29%	-1%	8%	70%
Waste, hazardous/ incinerated	**kg**	1 180.6	1 191.7	1 489.1	1 591.1	1 702.6	2 058.5
	% change with BC	0%	1%	26%	35%	44%	74%
			Emissions (Air)				
Greenhouse Gases in GWP100	**t CO2 eq.**	696.0	597.3	438.6	475.3	382.0	311.4
	% change with BC	0%	-14%	-37%	-32%	-45%	-55%
Ozone Depletion, emissions	**mg R-11 eq.**	0.0	0.0	0.0	0.0	0.0	0.0
	% change with BC	0%	0%	0%	0%	0%	0%
Acidification, emissions	**kg SO2 eq.**	4 234.0	3 666.4	2 893.3	2 927.0	2 437.3	2 327.1
	% change with BC	0%	-13%	-32%	-31%	-42%	-45%
Volatile Organic Compounds (VOC)	**kg**	7.4	6.6	5.8	6.4	5.8	5.8
	% change with BC	0%	-10%	-21%	-13%	-21%	-21%

life-cycle indicators per unit	unit	E0Ck	C0Ck	A0Ak	A0+Ck*	A0+Bk*	A0+Ak*
Persistent Organic Pollutants (POP)	**mg i-Teq**	167.3	156.7	149.5	186.3	180.6	185.2
	% change with BC	0%	-6%	-11%	11%	8%	11%
Heavy Metals	**g Ni eq.**	333.9	300.8	287.8	272.2	253.3	300.0
	% change with BC	0%	-10%	-14%	-18%	-24%	-10%
PAHs	**g Ni eq.**	66.1	65.0	88.2	62.2	69.0	55.1
	% change with BC	0%	-2%	34%	-6%	4%	-17%
Particulate Matter (PM, dust)	**kg**	191.7	187.1	215.1	226.9	235.2	268.9
	% change with BC	0%	-2%	12%	18%	23%	40%
Emissions (Water)							
Heavy Metals	**g Hg/20**	135.5	123.9	125.1	120.9	114.2	108.9
	% change with BC	0%	-9%	-8%	-11%	-16%	-20%
Eutrophication	**kg PO4**	1.4	1.4	1.8	1.8	2.0	2.5
	% change with BC	0%	0%	25%	30%	39%	74%
Persistent Organic Pollutants (POP)	**ng i-Teq**	0.0	0.0	0.0	0.0	0.0	0.0
	% change with BC	0%	0%	0%	0%	0%	0%
Economic indicators							
Electricity cost	**€**	276 949.01	235 894.19	166 443.11	182 495.26	142 503.87	109 562.50
	% change with BC	0%	-15%	-40%	-34%	-49%	-60%
Life-cycle cost	**€**	295 197.39	257 062.31	197 100.39	210 962.73	173 526.11	150 621.36
	% change with BC	0%	-13%	-33%	-29%	-41%	-49%

* amorphous steel core

Figure 6-13 below displays total energy, with total electricity consumption as a percentage of total energy consumption. As the results clearly show, electricity consumption and thus the use phase dominates energy consumption, representing greater than 88% for all options.

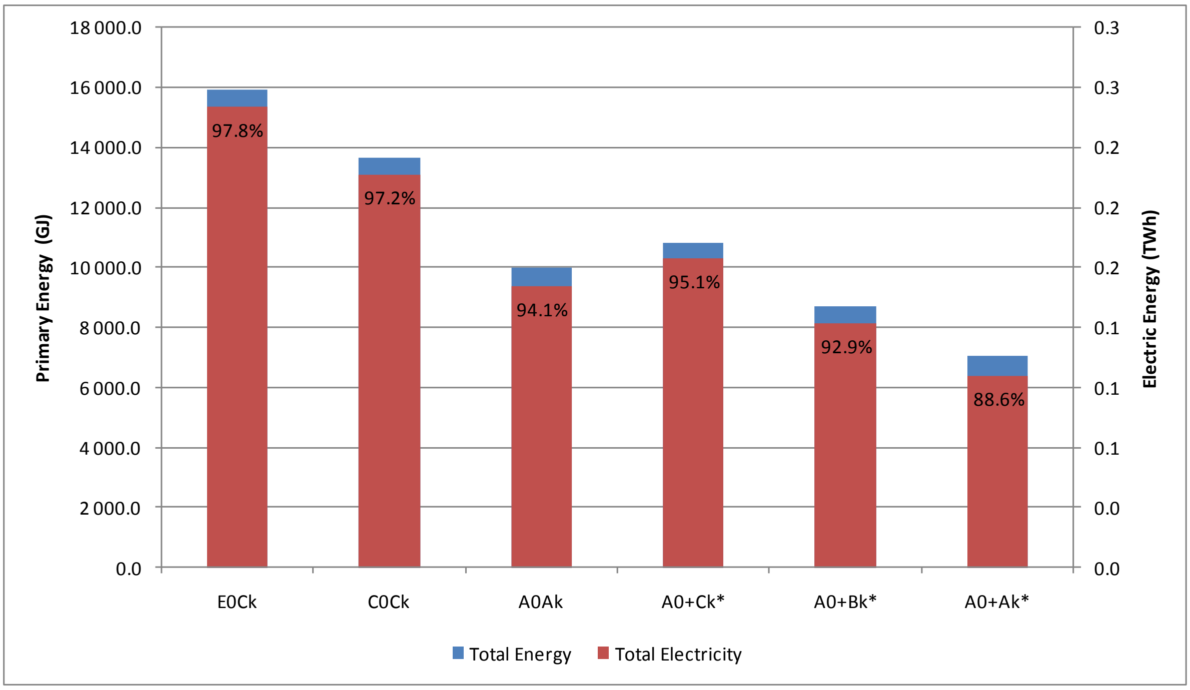

Figure 6-13: BC 5 Option 1 - Total energy and electricity consumption

Figure 6-14 shows product prices as a percentage of life-cycle costs. The part in blue represents electricity costs over the lifetime of the transformer. Product price represents 6-27% of life-cycle cost for these options, which is low compared to the other base-cases due to the high electricity prices used for DER transformers (0.3 €/kWh). As the figure shows, A0+Ak achieves least life-cycle cost of € 150 621.

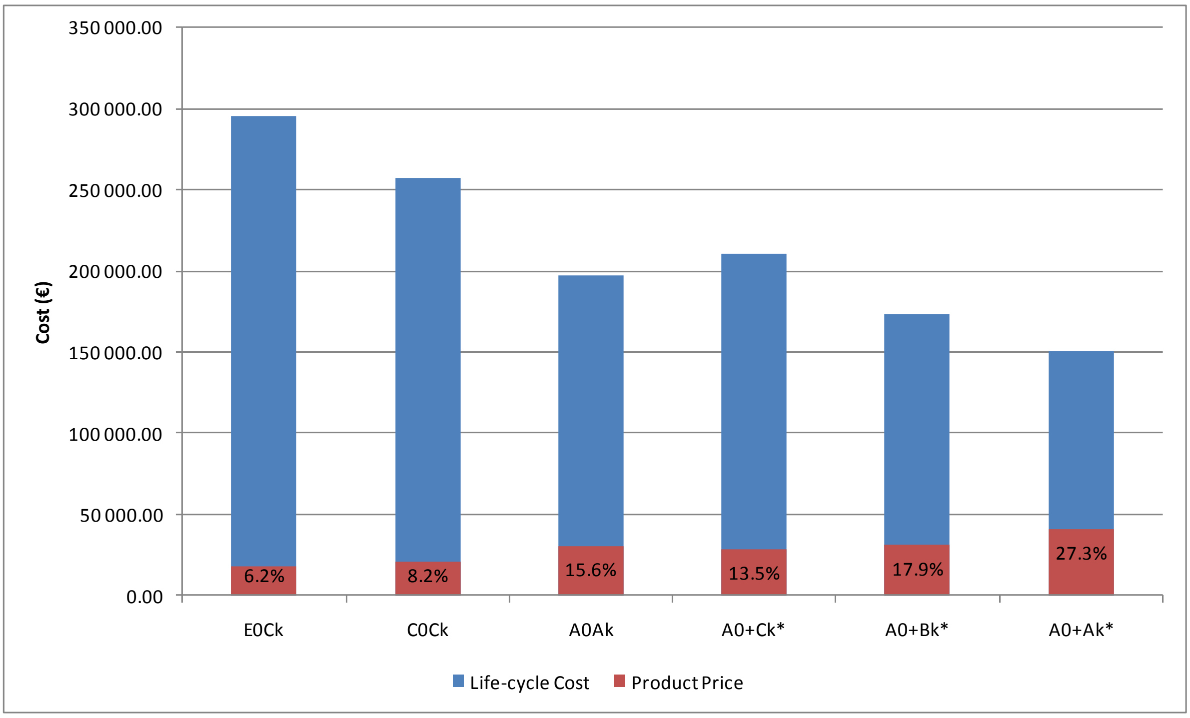

Figure 6-14: BC 5 Option 1 - Life-cycle cost and product price

Figure 6-15 compares total energy consumption with life-cycle cost in order to obtain a picture of how cost relates to general environmental performance. As the figure shows, the least life-cycle cost of A0+Ak is also the lowest energy consumption option.

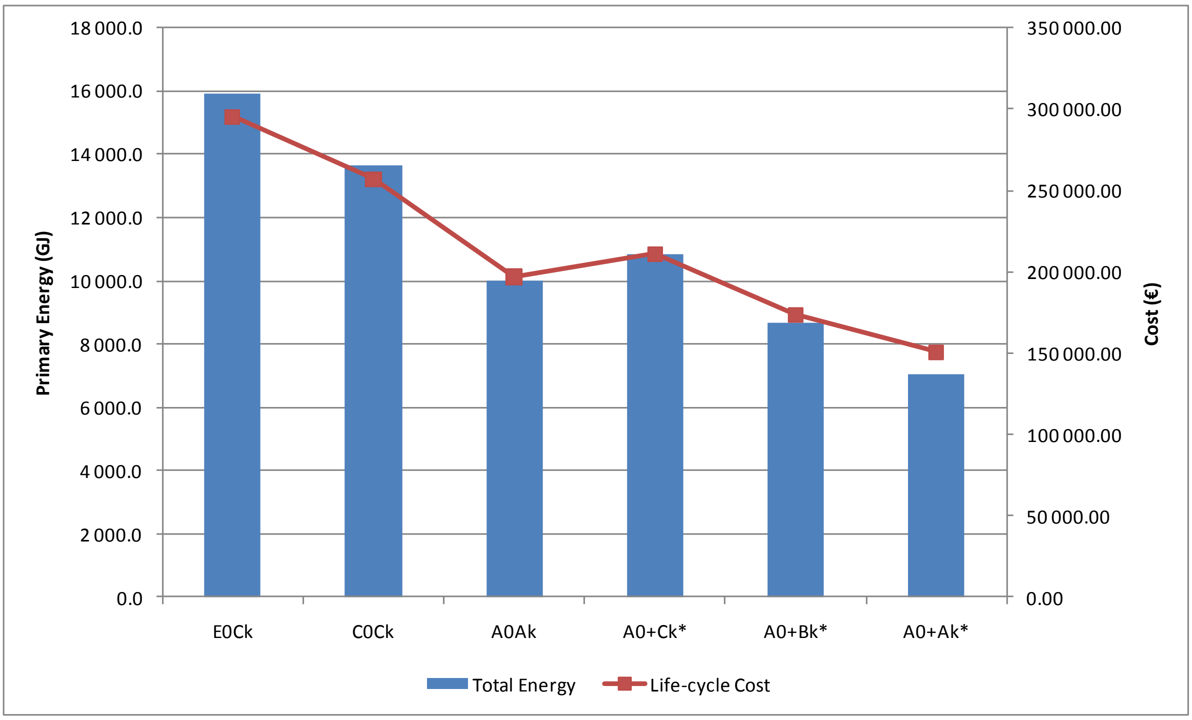

Figure 6-15: BC 5 Option 1 - Total energy consumption and life-cycle cost

6.2.1.6 Improvement options for BC 6: DER transformer dry-type 2 MVA

The results of the analysis of the improvement options for base-case 6 are seen below. As Table 6-22 shows, A0Ak provides the greatest improvement in terms of energy consumption (-23%), as well as attaining least life-cycle cost (-20%). However, in certain instances such as PAHs, particulate matter and eutrophication, the base-case achieves the least environmental impact, with option A0Ak achieving the greatest impact.

Table 6-22: BC 6 Option 1 - Indicators

life-cycle indicators per unit	unit	C0Bk	B0Bk	A0Ak
	Other resources and waste			
Total Energy (GER)	GJ	16 895.7	14 678.9	13 038.2
	% change with BC	0%	-13%	-23%
of which, electricity	primary GJ	16 443.8	14 156.7	12 445.8
	TWh	1.0	0.9	0.8
	% change with BC	0%	-14%	-24%
Water (process)	kL	1 095.4	942.7	828.6
	% change with BC	0%	-14%	-24%
Water (cooling)	kL	43 759.3	37 641.1	33 067.8
	% change with BC	0%	-14%	-24%
Waste, non-haz./ landfill	kg	29 463.2	28 572.5	28 118.0
	% change with BC	0%	-3%	-5%
Waste, hazardous/ incinerated	kg	552.6	534.6	517.2

	% change with BC	0%	-3%	-6%
Emissions (Air)				
Greenhouse Gases in GWP100	t CO2 eq.	741.6	645.5	574.6
	% change with BC	0%	-13%	-23%
Ozone Depletion, emissions	mg R-11 eq.	0.0	0.0	0.0
	% change with BC	0%	0%	0%
Acidification, emissions	kg SO2 eq.	4 333.2	3 755.3	3 333.1
	% change with BC	0%	-13%	-23%
Volatile Organic Compounds (VOC)	kg	7.0	6.3	5.8
	% change with BC	0%	-10%	-18%
Persistent Organic Pollutants (POP)	mg i-Teq	214.7	224.1	224.4
	% change with BC	0%	4%	5%
Heavy Metals	g Ni eq.	311.5	278.1	252.5
	% change with BC	0%	-11%	-19%
PAHs	g Ni eq.	115.3	113.3	129.7
	% change with BC	0%	-2%	13%
Particulate Matter (PM, dust)	kg	172.5	173.4	175.2
	% change with BC	0%	1%	2%
Emissions (Water)				
Heavy Metals	g Hg/20	151.1	140.8	138.5
	% change with BC	0%	-7%	-8%
Eutrophication	kg PO4	2.1	2.3	2.5
	% change with BC	0%	12%	19%
Persistent Organic Pollutants (POP)	ng i-Teq	0.0	0.0	0.0
	% change with BC	0%	0%	0%
Economic indicators				
Electricity cost	€	292 515.64	251 460.81	220 783.73
	% change with BC	0%	-14%	-25%
Life-cycle cost	€	320 707.37	283 599.39	257 714.91
	% change with BC	0%	-12%	-20%

Figure 6-16 below displays total energy, with total electricity consumption as a percentage of total energy consumption. As the results clearly show, electricity consumption and thus the use phase dominates energy consumption, representing greater than 95% for all options.

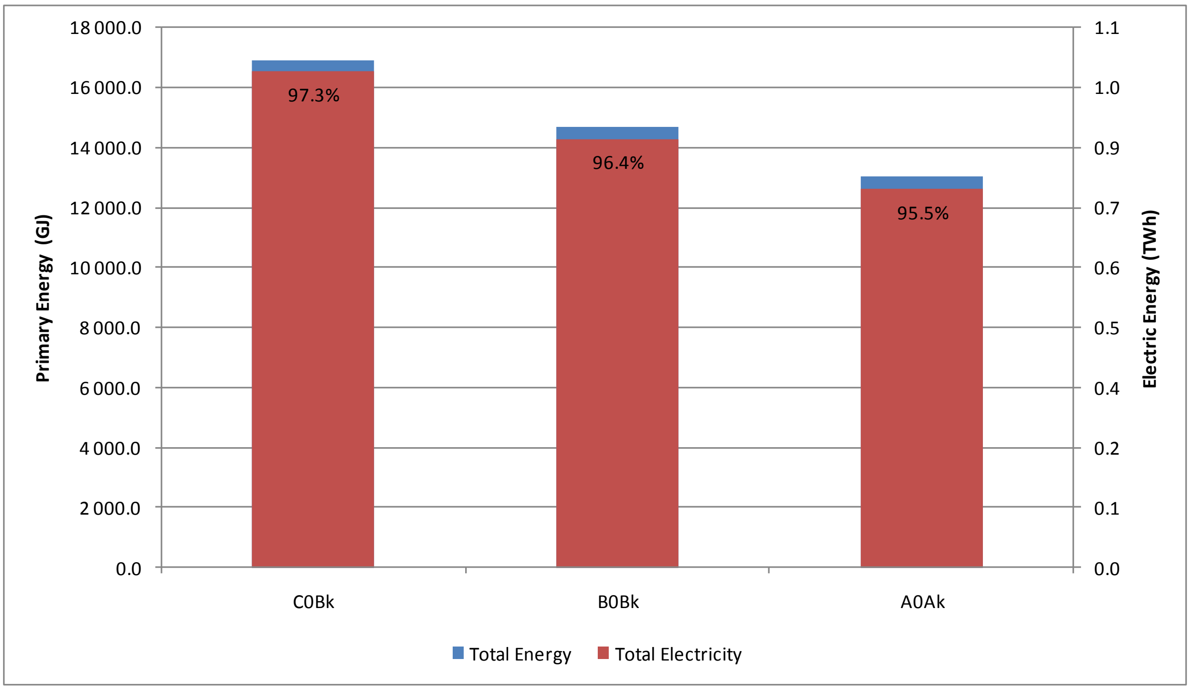

Figure 6-16: BC 6 Option 1 - Total energy and electricity consumption

Figure 6-17 shows product prices as a percentage of life-cycle costs. The part in blue represents electricity costs over the lifetime of the transformer. Product price represents 8-15% of life-cycle cost for these options, which is low compared to the other base-cases. As the figure shows, A0Ak achieves least life-cycle cost of € 257 715.