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Comparative Life Cycle Assessment of electric motors with different efficiency classes: A deep dive into the trade-offs between the life cycle stages in Ecodesign context

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Abstract

Purpose: Current ecodesign instruments usually focus on improving single life cycle stages, like the energy efficiency classes for motors put on the European market, which focus on the use stage. Resulting trade-offs between the life cycle stages are however often not integrated properly, like for instance trade-offs between manufacturing stage and use stage. Goal of this study was to evaluate the trade-offs between the additional efforts of producing energy-efficient motors (achieved e.g. via different materials for certain components) and the advantages gained from the improved efficiency in operation.

Methods: For this case study, Life Cycle Assessment methodology according to ISO 14040/44 was applied for the whole life cycle (cradle to grave) of three electric motors, each from a different efficiency class, and one serving as baseline. The motors under study have the following specifications in common: Asynchronous technology, 110 kW nominal power, cast iron series, 4-poles. To evaluate the use stage, two different operational profiles were studied for 20 years service life.

Results and discussion: The results clearly indicated the dominance of the use stage in the motors' life cycles and that an increase in efficiency pays off environmentally within the first month of operation in the applied load-time profiles. The dominating environmental impact categories, like ionizing radiation and global warming potential, relate to the consumption of electricity. The study results indicated also that the increase of the analyzed motors' efficiency encompasses trade-offs between the stages materials, manufacturing and end-of-life versus the use stage in regard to toxicity and (metal) resource depletion aspects; i.e. a burden-shifting between energy-related impacts and the toxicity- and resource depletion-related impacts.

Conclusions: In the analyzed study set-ups, including the modeled energy generation scenarios for Europe in 2050, an environmental break-even is achieved in less than a month in all impact categories except for human toxicity. Thus, the further improvement of energy efficiency of drive systems is and will stay a central ecodesign lever. However, toxicity and resource depletion trade-offs should be considered carefully within decision support and decision-making, and further research on related characterization models is necessary. Further, it is concluded that the load-time profile as well as the motors' service life have a high influence, and therefore designing drive systems in context with the application seems to be an important approach to facilitate ecodesign.

Keywords: Life Cycle Assessment, electric motors, ecodesign, energy efficiency.

1 Introduction

Global warming has to be limited to well below 2°C compared to the average temperature in pre-industrial times to prevent the most severe impacts of climate change and possibly catastrophic changes in the global environment. This was agreed by almost all countries worldwide in 1992 under the United Nations Framework Convention on Climate Change (UNFCCC) and just recently tightened through the agreement in Paris at the of end 2015 [COP21]. To achieve this, the world must stop the increase in greenhouse gas emissions by 2020 and reduce them by 60% by 2050 compared with 2010 [COM 2010]. The 2020 climate and energy package is a set of binding legislation to ensure the EU meets its climate and energy targets for the year 2020. The targets were set by EU leaders in 2007 and enacted in legislation in 2009. They are also headline targets of the Europe 2020 strategy for smart, sustainable and inclusive growth [EC 2020].

As an accompanying legislative act, the “Energy using products directive” as well as its successor the “Energy-related products directive”, referred to as Ecodesign Directive, were issued [EU 2009]. Resulting from this, a first study concerning the energy usage of branches and associated technologies was conducted and work plans [COM 2008; SWD 2012], prioritizing products under the scope of the directive, were issued. Electric motors use almost 50% of the electricity in Europe in applications like elevators, cranes and cooling systems. More efficient motors could save Europe then around 135 TWh of electricity by 2020 – equivalent to the annual electricity consumption of Sweden – and correspondingly 60 million tons of CO_2 emissions [EC 2014]. Therefore electric motors were addressed within the first work plan and resulting from the conducted preparatory study was a product specific regulation, regulating the efficiency levels of motors to be put on the market of EEA [EU, 2014]. Then in 2015 the European Commission issued the Circular Economy Package (CEP) [EC 2015], following the European Resource Efficiency Roadmap [EC, 2011a; EC, 2011b], which adds another dimension to the subject by aiming at improving resource and material utilization by various measures, including among others a standardization request for material efficiency standards [EC 2015b]. A consequence might be a dilemma of balancing energy efficiency for the sake of mitigating climate change and associated risks versus material (or resource) efficiency mitigating resource depletion and economic risks resulting from scarcities. Since up to now there are, besides the preparatory studies associated with ErP directive (e.g. [Almeida 2008], [Almeida 2014]) applying the so-called MEEuP [VHK 2005] and MEErP [MEERP 2015] Methodology for evaluating ecodesign levers, there are no detailed assessments of electric motors available, the present study aims at assessing the trade-offs between the additional efforts at the materials and manufacturing stages needed to achieve the higher efficiency levels in the use stage by the means of the Life Cycle Assessment (LCA) methodology and to then evaluate and discuss environmental hotspots. For that, 3 motors of a defined type – 4 poles, cast iron series – but with different efficiency levels (IE2, IE3 and IE4) will be assessed.

The paper is structured as follows: Chapter 2, the methods section, describes the applied method LCA and its framework; Chapter 3, describes the Life Cycle Inventory (LCI) and the results of Life Cycle Impact Assessment (LCIA) per life cycle stage, as well as summarized them in a comparative view; Chapter 4 then interprets and discusses the results of the LCIA and follows up the findings in terms of sensitivity checks; Chapter 5 finally concludes on the results of the case study.

2 Method: Life Cycle Assessment

The underlying methodology is the life cycle assessment (LCA) methodology as laid out in [ISO 14040, ISO 14044], following the principles described in the “ILCD handbook” [ILCD 2010], using the impact indicators and characterization models as recommended by the EC JRC for usage in EU policy context [ILCD 2011]. Additionally the so called product category rules (PCR) for motor systems were taken into account, as described in [EN50598-3]. For the modelling GABI6 and the GABI life cycle inventory database supplied by thinkstep AG were used.

2.1 Goal & Scope

The study aims to compare the potential environmental impacts of motors of one product family (same technology, same product type, same power rating) with different efficiency classes over the whole life cycle in the current European context of the EcoDesign Directive and the Circular Economy Package. The goal is to evaluate the trade-off between the materials & manufacturing stage (more copper, higher grade electrical steel etc.) and usage (less power consumption through higher efficiency) in detail and to additionally conduct a hot spot analysis, which results may be used internal in product design.

2.2 Assumptions & Limitations

Important part of a LCA case study report is to state taken assumptions and identified limitations that have to be considered when interpreting and conclusion on the results. In the context of this case study the following should be taken into account:

(1) Bill of Materials were only available for the complete motors and not for their components (part level), therefore certain limitations apply concerning manufacturing steps for these components. On the other hand it has to be considered that for most of the materials typical, appropriate manufacturing steps (semi-finished goods) can be assigned. In this context , the assignment of the generic (background) datasets to the materials should also be recognized as of high importance to robust results. Anyhow these limitations will apply to all assessed products in the same way. Transportation of the materials to the factory were not considered in detail due to a lack of robust, precise data and a rather complex supply chain from the ore to the semi-finished goods and components needed for assembly. It was assumed to be not significant, based on internal ecodesign and LCA case studies and anyhow a lot of transport related data is already included in the applied background datasets. The distribution stage of the final product was considered to exclude it from having significant contribution to environmental impacts.

(2) Energy usage for the assembly had to be allocated based on working hours, which means that we allocated a mean energy consumption per production working hour, based on the metering of primary and secondary energy meters of the factory for one year, along the production working hours needed for a motor of this type. Based on comparison of certain production steps with literature and generic data sets, it is known to have a high level of uncertainty due to a rather complex facility infrastructure with a lot of consumers not directly linked to the production of the products. The working hours for assembly were assumed to be independent of the efficiency class of the motor (not major change of technology), whereas higher efforts, e.g. energy, needed for the utilization of more material (or higher grade material) were included in the secondary data, the

datasets of the materials and parts assigned. This assumptions and limitations again will affect all motors in the same manner and hence not affect the comparative assessment. The applied generic usage scenarios were representative but not application specific; therefore the results may vary in other scenarios including different load-time profiles as well as different regional specifics like the electricity mix. The chosen scenarios are intended to give an idea about the variability of the use stage and its influence on the associated environmental impacts.

(3) For the end-of-life stage, which was assumed to take place in Europe due to usage in Europe, a generic end-of-life-scenario was derived based on [Kasper et al., 2015] and [IEC/TR 62635]. It is assumed that the main parts of the motor will be disassembled, then shredded, followed by material separation by respective technologies using physical properties (magnetic, density) routing metals into recycling processes and plastics to energy recovery process. Others were assumed to be finally be landfilled. Respective recycling and recovery quotes were drawn from the generic datasets for end-of-life treatment.

This has to be considered when concluding on the results. The case study will only display results according to this specific set-up and can’t be generalized to all applications on global scale, especially concerning the impacts associated with electricity generation and the contemporary grid mixes in the various regions in the world.

2.3 Function, functional unit and reference flow

Main purpose of an electrical motor is to convert electrical power into mechanical power for various applications, e.g. conveyor belts, pumps, fans. The energy conversion can be realized by different types of technology, for instance asynchronous or synchronous to the net frequency and corresponding product designs. Usually each of these technologies does have its advantages and disadvantages in context to the application. One key point in any case is the efficiency of this energy conversion. The products under study are Siemens motors of type Simotics SD basic, cast iron series, 4-poles, 50 Hz, self-ventilated with the international efficiency (IE) classes IE2, IE3, IE4, whereas the efficiency classes are defined in [IEC 60034-30-1].

The functional unit (FU) was defined as the provision of mechanical power in an applied usage scenario (operation profile, load-time profile) by electrical motors with 110 kW nominal power at 365 days a year in 20 years of service life. For the two applied usage scenarios, which are described in detail in chapter 3.2, the reference FU, used in the comparative assessment and derived from the corresponding output (mechanical power) of the motor with efficiency class IE2, was defined as:

(1) Scenario A): High duty - Provision of 15,658,500 kW nominal power;

(2) Scenario B): Low duty - Provision of 8,431,500 kW nominal power.

The reference flow was determined as [kg] of electrical motor (baseline IE2-motor: 707 kg, range up to 744 kg for IE4-motor).

2.4 System boundaries and cut-off criteria

The assessment includes all life cycle stages from cradle to grave. The system boundaries were defined according to EN50598-3, also taking into account the defined parameters, like for end-of-life. The manufacturing stage includes all processes associated with producing the motor, from the upstream processes such as mining of metal ores and extraction of crude oil, to the final assembly of the motor, including forming processes for the semi-finished goods, like stamping, bending, die casting and impregnation / insulation. Figure 1 schematically displays the set system boundaries including the background and foreground data.

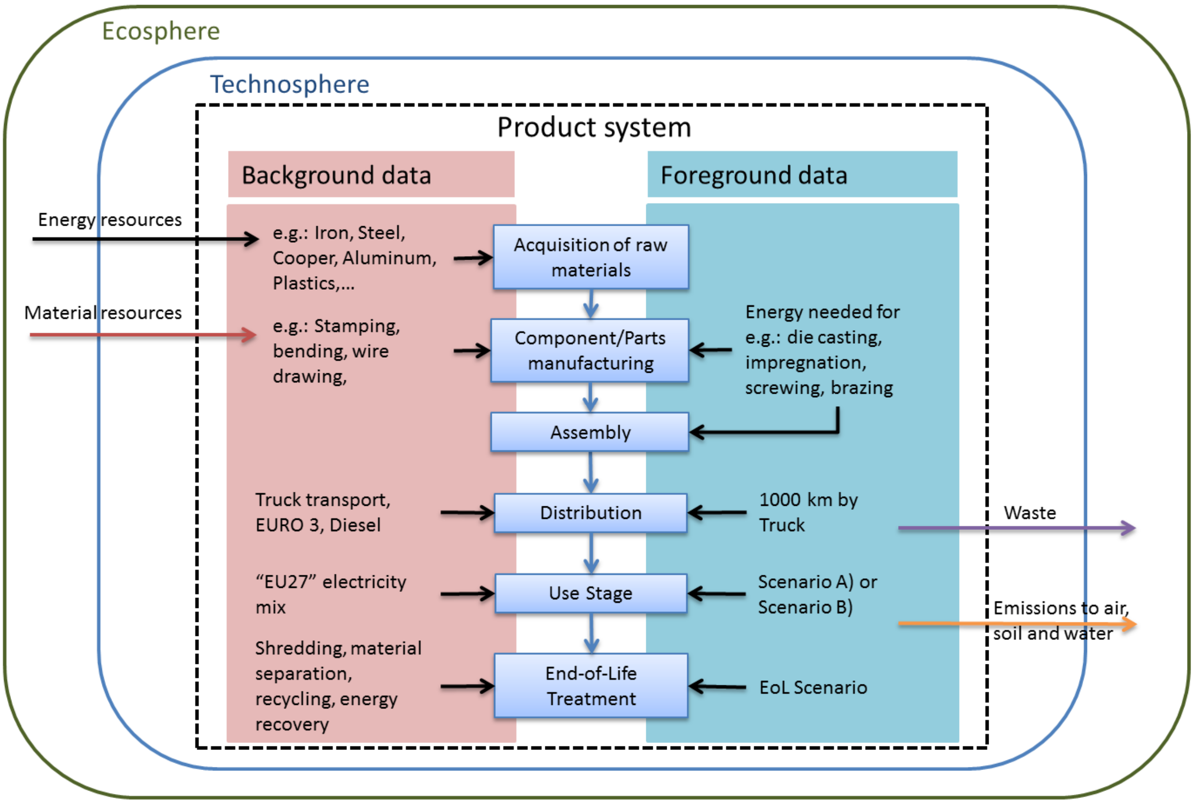


Figure 1: Graphically display of the system boundaries of the LCA case study to evaluate the environmental performance and potential trade-offs between motors with different efficiency classes in two different usage scenarios.

For final assembly (e.g. screwing), die casting and impregnation, the energy consumption has been allocated to the motor based on the factory's reported data from 2011, see subchapter 2.2. For the other processes generic data (e.g. punching, bending, wire drawing, coating…), as available in the corresponding tool and database, were used. Distribution has been considered as 1000 km truck transport within Europe. Not considered were the transport of materials to production site, initial sample tests, all activities concerning the superstructure (building of and maintenance of the production facilities, tools and machines), and resources for R&D, planning and sales. No further cut-off criteria were applied.

2.5 LCI modelling framework

Based on the defined decision context, the modelling framework of this study is set to the attributional principle, depicting the existing value chain, i.e. use the current state of the art data of the modelled system. For instance the German electricity grid mix is used for the motor production, since it’s build in Germany, the EU27 electricity was used for the assessment of the use stage, as well as end of life processing because the location of the application is assumed to be “somewhere in Europe” (see also subchapter 2.1). Multifunctionality of processes is solved using allocation based on physical properties (weight) and economic data (working hours). In this context it shall be considered that the systems basically do not have secondary functions to providing mechanical power and any occurring problems of multifunctionality of the product systems in manufacturing and end-of-life are handled in the same way.

2.6 Data quality requirements

Generic data was checked to fulfil the “ILCD requirements” on data quality (or in other words “ILCD compliance”). In regards to managing uncertainty, no specific limit of the variance of the inventory data was set. In this context it has to be considered that the major goal is a non-assertive comparative analysis of electrical motors with different IE-classes, hence in terms of data quality, the data differentiating the systems (Material composition and energy consumption at the use stage) is mainly important and was therefore directly drawn out of technical data systems and product documentation. Other uncertainties, choices and assumptions will apply to all systems under study in a similar way and can therefore be neglected.

2.6.1 Technological representativeness

The technology of the electrical motors, the material composition of the product respectively, and their production processes is based on Siemens technology. It’s supposed to be quite similar to the technologies used by other motor manufactures in Europe and therefore representative of the current state of the art.

2.6.2 Geographical representativeness

As explained in the introduction, the goal of the study was to reflect the European situation; hence the use stage should represent the European average (e.g. electricity mix). Data for manufacturing (assembly, parts manufacturing) should reflect the German situation since the motors under study, corresponding to the applied product standards are intended for applications in the European Economcy Area (EEA), are produced in Germany. Concerning the materials stage, global data sets should be applied since the associated supply chain is not defined in regard to geographic origin.

2.6.3 Temporal representativeness

This kind of electrical motors with 110 kW is usually utilized, depending to some extend on the influence of application environment (e.g. dust, corrosive atmosphere, mechanical stress), for about 20 years and rated as investment goods. The innovation cycle is around 7 – 10 years, whereas the development of the next generation will take approximately about 4 years, depending a lot on the needed certifications, tests and approbations for the usage. In the last years (last product redesigns) there has been no major change in the manufacturing processes or product technologies, therefore data from 2010 to 2015 can be seen as being temporal representative for the case study. Given the current development of the underlying data, the case study can be seen as valid for up to 5 years. After that period the results have to be reviewed in context to technological changes, especially concerning the environmental impacts associated with the electricity generation and distribution, which – due to the shift to renewable energy sources – will likely change to lower scores.

2.7 Life cycle impact assessment methods

For the life cycle impact assessment (LCIA) the midpoint characterization methods recommended by the European Commission's Joint Research Center (JRC), Institute for Environment and Sustainability, published as part of the ILCD handbook are used [ILCD 2011]. These are also used in the context of the Product Environmental Footprint (PEF) initiative by the European Commission and therefore currently very relevant to industry, due to a potential application in policies. Internal and external normalization was applied to support the interpretation of the LCIA results, by relating the LCIA scores to defined bases. Consequentially for external normalization the Normalization Factors (NF) per Person (PE = Person Equivalents) as defined in the PEF guide for the products are used, which relate the LCIA results to the European domestic inventory in 2010. Per person normalization factors (Person Equivalents) have been calculated using Eurostat data on EU 27 population in 2010. Characterization methods and NF are listed in Table 1 below [EC 2016]. Further following the PEF guide, weighting currently is applied using the weighting factor 1 for all impact categories.

Table 1: Characterization methods applied in the study, as recommended by ILCD for life cycle assessments in European policy context. The normalization factors (NF) as Person Equivalents (PE) are taken from the PEF guide for pilot studies [PEF 2016].

Abbreviation	**Characterization methods and models**	**Unit**	**Normalisation Factor (NF)**
TE	Terrestrial eutrophication, Accumulated Exceedance model	molc N eq	1.76E+02
FE	Freshwater eutrophication, EUTREND Modell, ReCiPe	kg P eq	1.48E+00
ME	Marine eutrophication, EUTREND Modell, ReCiPe	kg N eq	1.69E+01
PM	Particulate matter, RiskPoll	kg PM2.5 eq	3.80E+00

PCOF	Photochemical ozone formation, LOTOS-EUROS Modell, ReCiPe	kg NMVOC eq	3.17E+01
RD, w	Total freshwater consumption / Resource Depletion – water, UBP 2006	UBP	8.14E+01
HT, c	Human toxicity, cancer effects, USEtox	CTUh	3.69E-05
HT, nc	Human toxicity, non-cancer effects, USEtox	CTUh	5.33E-04
IR	Ionizing Radiation – human health effects, ReCiPe	kg U235 eq	1.13E+03
GWP	IPCC global warming, w biogenetic CO$_2$	kg CO$_2$ eq.	9.22E+03
ET, f	Ecotoxicity – aquatic, freshwater, USEtox	CTUe	8.74E+03
OD	Ozone depletion, WMO Modell, ReCiPe	kg CFC-11 eq	2.16E-02
RD, f+m	Resource depletion - fossil and mineral, CML 2002	kg Sb eq.	1.01E-01
A	Acidification, Accumulated Exceedance model	mol H+ eq	4.73E+01

It should be noted that, corresponding to the reference [ILCD 2011], certain characterization methods – even though being recommended – still are rated with Level III for data quality and should therefore be considered with caution in interpretation. The same caution should also be taken when drawing conclusions from normalized LCIA scores. Normalization is needed to enable the comparison across impact categories, but external normalization is questionable as potential normalization bases still lack political and scientific consensus concerning the so-called areas of protection (environment, resources, toxicity) [Bjørn and Hauschild, 2015].

3 Life Cycle Inventory

The following chapter describes the key aspects of each life cycle stage in the life cycle inventory phase of the LCA.

3.1 Materials and manufacturing stage

Key aspect to potential environmental and toxicity impacts of electrical motors, being electromechanical products, is the material composition. Processes for extracting ore out of earth and making “usable”, raw material out of it, are the drivers of environmental effects like acidification or global warming, as well as related effects like resource depletion [Hermann et al., 2012]. For this case study the material composition of the parts of an electrical motor were summarized to certain material groups, resulting in the material composition of the motors of different international efficiency (IE) classes as displayed in Table 2 below. The IE classes are defined in IEC 60034-30-1:2014, from IE2 (high efficiency) to IE4 (super premium efficiency. The table also includes assigned generic processes from the Gabi database.

Table 2: Material composition of the motors with different IE classes. The IE2-motor is the reference for the percentages displaying the increase for certain material groups when the efficiency is increased.

Material group (assigned generic treatment processes)	IE2	IE3	IE4
Electric sheets (stamping)	271 kg	10%	10%
Cast Iron (die casting)	271 kg	0%	0%
Copper (wire drawing)	69 kg	4%	10%
Other Steel (stamping and bending)	64 kg	0%	0%
Packaging Material (wooden pallet production)	24 kg	0%	0%
Aluminum (extruding)	19 kg	5%	5%

Impregnation Resin	5 kg	20%	20%
Others: Other materials with mass below 5 kg and no difference between the IE classes: Plastics (injection molding), Insulation, Paint (painting), Rubber, Brass (stamping and bending), Solder (brazing) & Grease	9,8 kg	0%	0%

Figure 2 displays the material fractions that have been increased in quantity to reach the higher efficiency levels accordingly. These material groups then have been matched to a corresponding, most representative LCI processes in GABI, reflecting the inputs, like crude oil or copper ore, and outputs, like CO_2-emissions or metal scrap, of this manufacturing step.

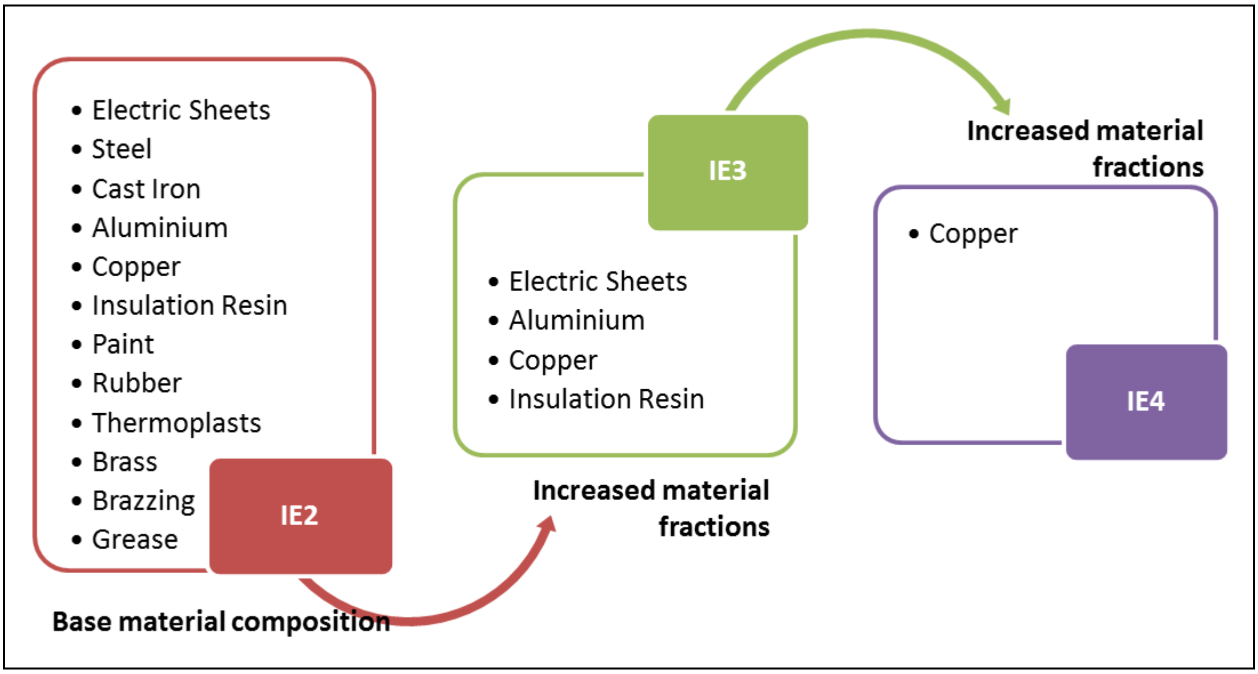


Figure 2: Display of material fractions increased, from the base material composition of an international efficiency class 2 (IE2, high efficiency) motor, to achieve higher efficiency levels: International efficiency class 3 (premium efficiency) and 4 (super premium efficiency) as defined in IEC 60034-1-30. No material fractions decrease in this regard.

After this, the most representative machining or treatment process, like wire drawing or die casting (see also Table 2), is added to the material group to reflect the aspects of the finishing processes, including energy consumption and typical material losses as available in the generic data sets. To finally finish the model of motor manufacturing, the last step added is the final assembly. The energy consumption for assembly, including varnishing/impregnation was approximated based on an allocation of the 2011 annual energy consumption by working hours. Parts or material transport is only included as far as reflected in the generic data.

Distribution of the final product to the usage location is considered by transportation by truck (consuming diesel) and a distance of 1000 km.

3.2 Use stage

The use stage is known in drives for being the (by far) most relevant, because of the purpose of the functionality of transferring electrical energy into mechanical power. Use stage in drives, including motors, is characterized by an operating profile, defined by the time fraction the component is operating at specific operating points [EN 50598-1, EN50598-2]. These operating points of motors are characterized by the motor's load at a certain speed in percent of their nominal values. Further the motor's efficiency (or rather the losses) depends on these values (load, speed) and is therefore specific for the operating points. The operating or load-time profile itself puts them then into context to a defined amount of time, e.g. the time fraction the motor runs at the specific operating point in the applied use scenario [Auer and Weis, 2014]. Operating profiles, in principle displayed in Figure 3 can roughly be distinguished into two types:

- Fixed speed operation – Applications with a constant load and speed, e.g. simple conveyor belts;
- Variable speed operation – Applications with variable load and speed, e.g. centrifugal pumps with variable flow.

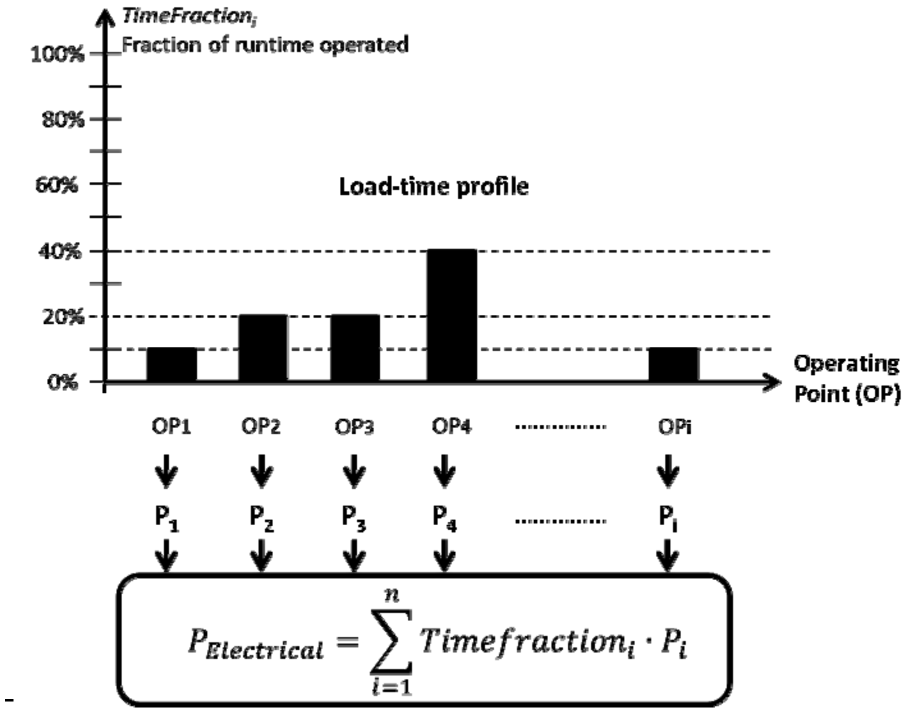


Figure 3: Typical power required by application over time fraction = load-time profile required to calculate the electrical energy needed.

For this case study, two application scenarios were defined by the means of operating profiles and a reference service life, to evaluate the use stage and the potential environmental improvements through higher efficiency levels. The two scenarios, displayed in Figure 4, were chosen to take into account a high duty, Scenario A), and a low duty operation, Scenario B), and to reflect the results then in this context. Both scenarios are basically variable speed operations, which are more common for motors with power ratings corresponding to the ones of this case study [Almeida 2014].

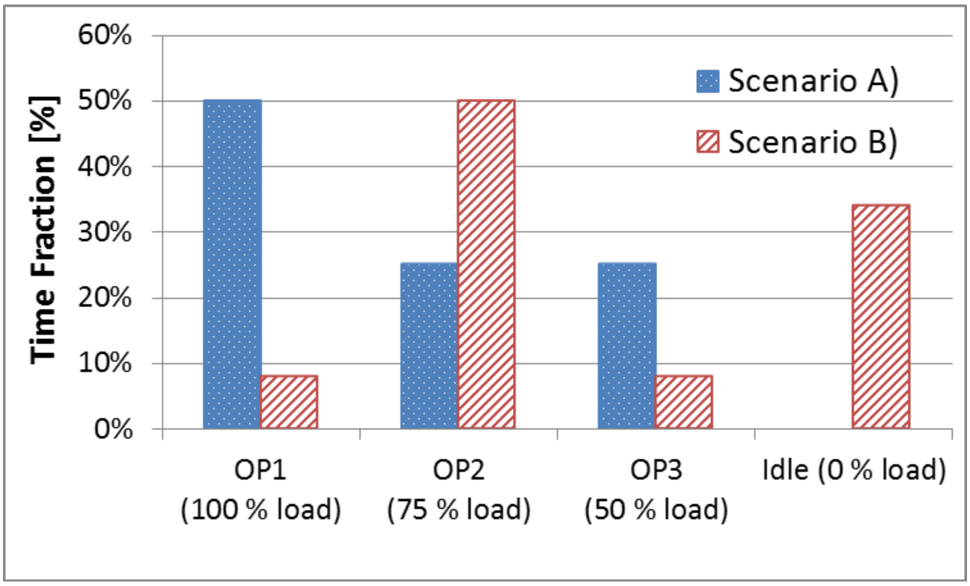


Figure 4: Graphical display of the two operating profiles corresponding to Scenario A) and Scenario B) applied in the case study.

The relevant parameters (speed, load and time fraction) of the two scenarios are displayed in Table 3; Table 4 lists the corresponding efficiencies of the motors of the different IE-classes, at the respective operating points.. For the reference of the comparative assessment, the IE2-motor, this then corresponds to the respectively defined functional unit laid down in the goal and scope (subchapter 2.3).

Table 3: Relevant parameters of two use stage scenarios applied in the LCA of the motors with different efficiency (IE) classes. The scenarios are characterized by an operating profile, i.e. the amount of time (percent of 24 h) the motor works at specific operating points (OP). The OP is characterized by the speed and load of the motor in terms of percentage of their nominal values.

Usage: Scenario A) / calculation scheme				
load	**speed [%]**	**load [%]**	**time [%]**	**time [h]**
operating point 1 (OP1)	100	100	50	12
operating point 2 (OP2)	100	75	25	6
operating point 3 (OP3)	100	50	25	6
Idle	0	0	0	0
Usage Scenario B) / calculation scheme				

load	**speed [%]**	**load [%]**	**time [%]**	**time [h]**
operating point 1 (OP1)	100	100	~8	2
operating point 2 (OP2)	100	75	50	12
operating point 3 (OP3)	100	50	~8	2
Idle	0	0	34	8

Table 4: Efficiencies of motors with different IE-classes at the operating points (OP) corresponding to Table 3.

Product, Efficiency [%] at OPs	**OP1**	**OP2**	**OP3**
Motor 1 (IE2)	94	94,6	94,5
Motor 2 (IE3)	95,5	95,8	95,4
Motor 3 (IE4)	96,4	96,6	96,3

The input flow of electrical energy was fed by “EU27 power mix”, as the currently available European average in the GABI database.

3.3 End-of-life stage

For end-of-life stage, current available technologies and (pre-)treatment steps are combined to a most likely, representative scenario based on [Kasper et al., 2015] and [IEC/TR 62635], an internal research project [Süß, 2007], and discussions in an European work group for motors, currently developing PCR for LCA of motors [CLC TC2 WG2], aligned EN50598-3. For the case study the scenario was defined as follows: The whole motor is disassembled into the main parts (housing, stator, rotor, windings), which are then shredded. This is then followed by material separation by physical properties, e.g. eddy-current and density, routing the different fractions to material recycling (metals, wood), energy recovery (insulation/impregnation, plastics) and landfill (ceramics, recovery/recycling process losses). 5 % of losses were assumed for recovery and separation processes, whereas generic datasets were used for recycling, recovery and landfilling processes, including material specific recycling quotes and further necessary inputs.. Crosschecking with [Almeida 2008], [Almeida 2014] and [Karlsson and Järrhed, 2000], this approach and the corresponding, high recycling quotes (~ 95 %) were assumed to be realistic. Potential credits, through the avoidance of virgin metals production and/or energy recovery through polymer materials, are then displayed as in the LCIA results for end-of-life stage; this means that there was no direct crediting to other life cycle stages within the model.

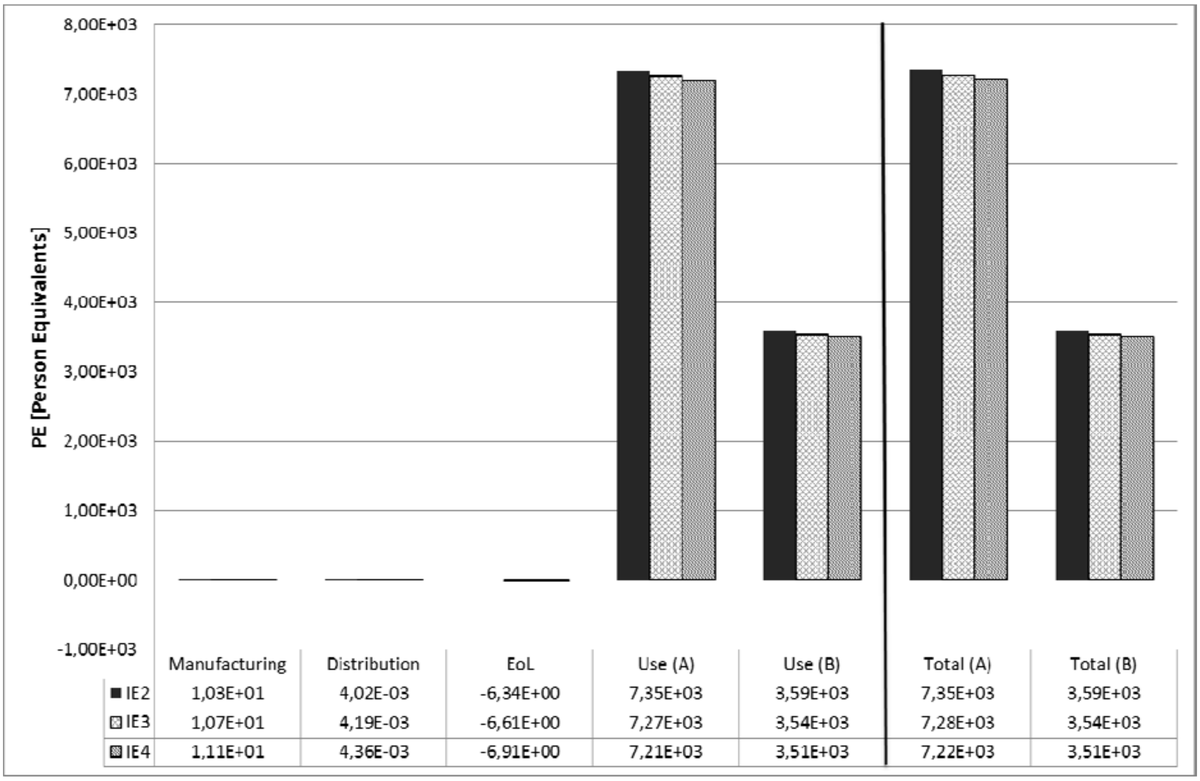
4 Life Cycle Impact Assessment

The following chapter now describes the results of the life cycle impact assessment, whereas their interpretation and discussion will follow in chapter 5.

4.1 Life cycle impacts

The results of the life cycle impact assessment with applied external normalization and weighting, using the normalization and weighting factors of the PEF guide for pilot studies (Version 1.6), for each of the motor types and life cycle stages for both usage scenarios are displayed in Figure 5.

Looking at the impact scores displayed, at first it can be stated, that the use stage is by far the most relevant life cycle stage, as the other life cycle stages are not visible in this scale. Secondly it can be seen that for both scenarios the increase in the motors’ efficiency reduces the environmental impacts expressed in PE.



	Manufacturing	Distribution	EoL	Use (A)	Use (B)	Total (A)	Total (B)
■ IE2	1,03E+01	4,02E-03	-6,34E+00	7,35E+03	3,59E+03	7,35E+03	3,59E+03
▨ IE3	1,07E+01	4,19E-03	-6,61E+00	7,27E+03	3,54E+03	7,28E+03	3,54E+03
▨ IE4	1,11E+01	4,36E-03	-6,91E+00	7,21E+03	3,51E+03	7,22E+03	3,51E+03

Figure 5: Externally normalized, weighted and aggregated LCIA scores in terms of Person Equivalents (PE) for the 3 electric motor types (IE2, IE3 and IE4).

Figure 6 now displays the data in PE per impact category. Based on this, it can be determined that the most relevant impact categories for electric motors are ionizing radiation (IR), water depletion (RD, w), and global warming potential (GWP), and all these are predominantly driven by the amount of electricity that is converted in the use stage of the motors.

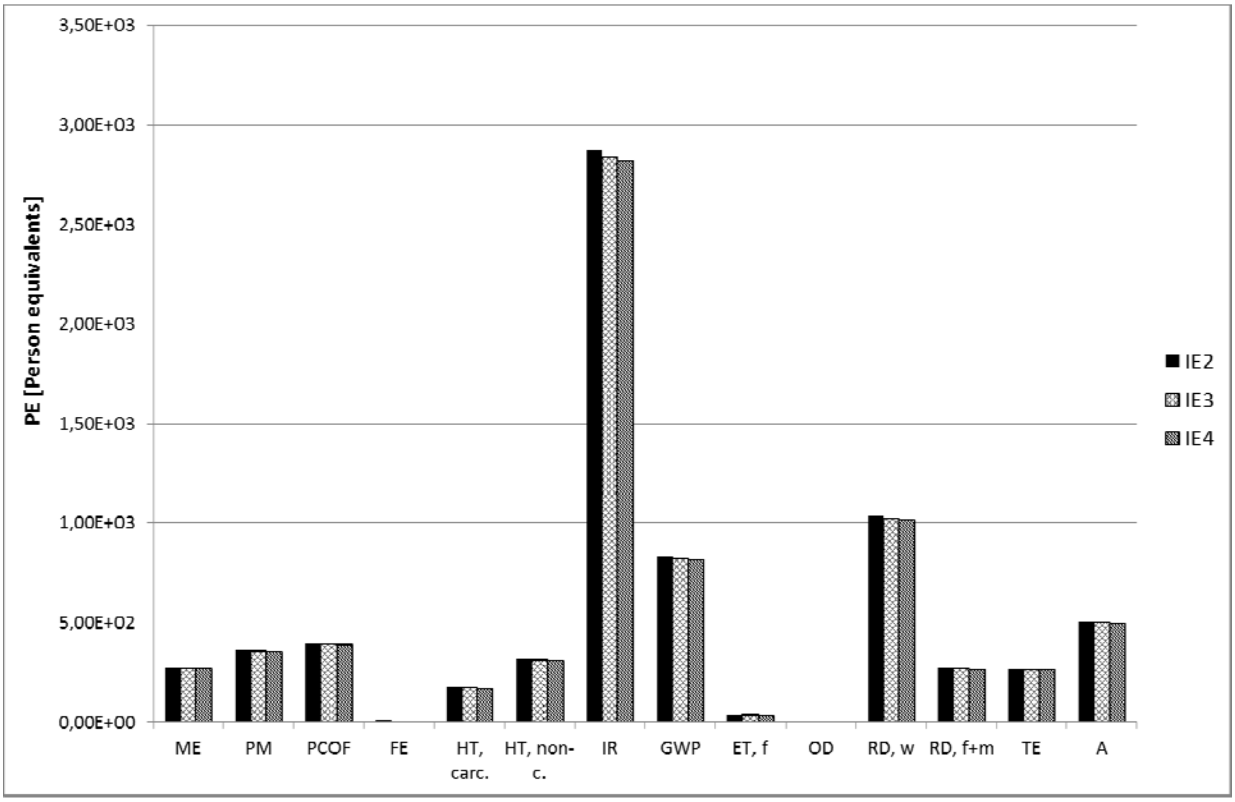


Figure 6: LCIA scores of the motors, summarized over the whole life cycle,). (impact categories on x-axis according to Table 3).

To have a better view on the results of the manufacturing stage (comprising also the materials production, cf. section 2.4), the LCIA scores are displayed in Figure 7 without the dominating use stage, i.e. only for manufacturing, distribution and end-of-life.

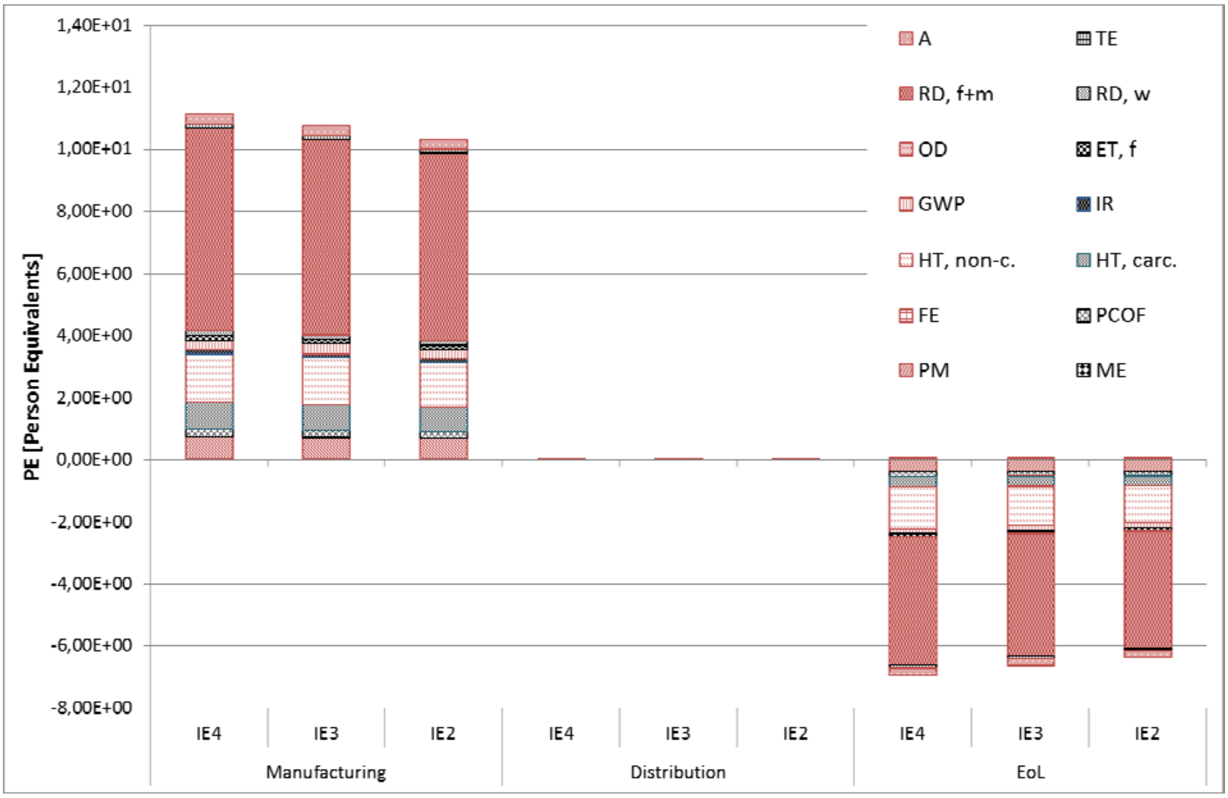


Figure 7: LCIA scores of manufacturing, distribution and end-of-life of the motors in PE.

Looking at this figure, it can be seen that the distribution of the contribution of the analyzed impact categories to the total score in PE is more-or-less comparable between the different motors. The small differences that are observed can be assigned to the change in the material composition between the motors. Secondly it can be seen, that the EoL stage corresponds to the manufacturing stage, which means on the one hand that due to the motors composition of mainly metals, the high recycling quotes theoretically compensate more than half of the impacts from manufacturing and material stage and therefore the increase in impacts with the higher energy efficiency are also partly compensated by a higher benefit from recycling. Thirdly, the figure shows that the distribution stage is indeed insignificant. Lastly, the figure also shows that fossil and mineral resource depletion, human toxicity and particulate matter are the most relevant impact categories at the manufacturing and end-of-life stages.

To evaluate the respective drivers at manufacturing stage, Figure 8 now shows these main impact categories, as well as the global warming and acidification potentials, and their respective contributors at the manufacturing stage of the IE4-motor in 100%-view

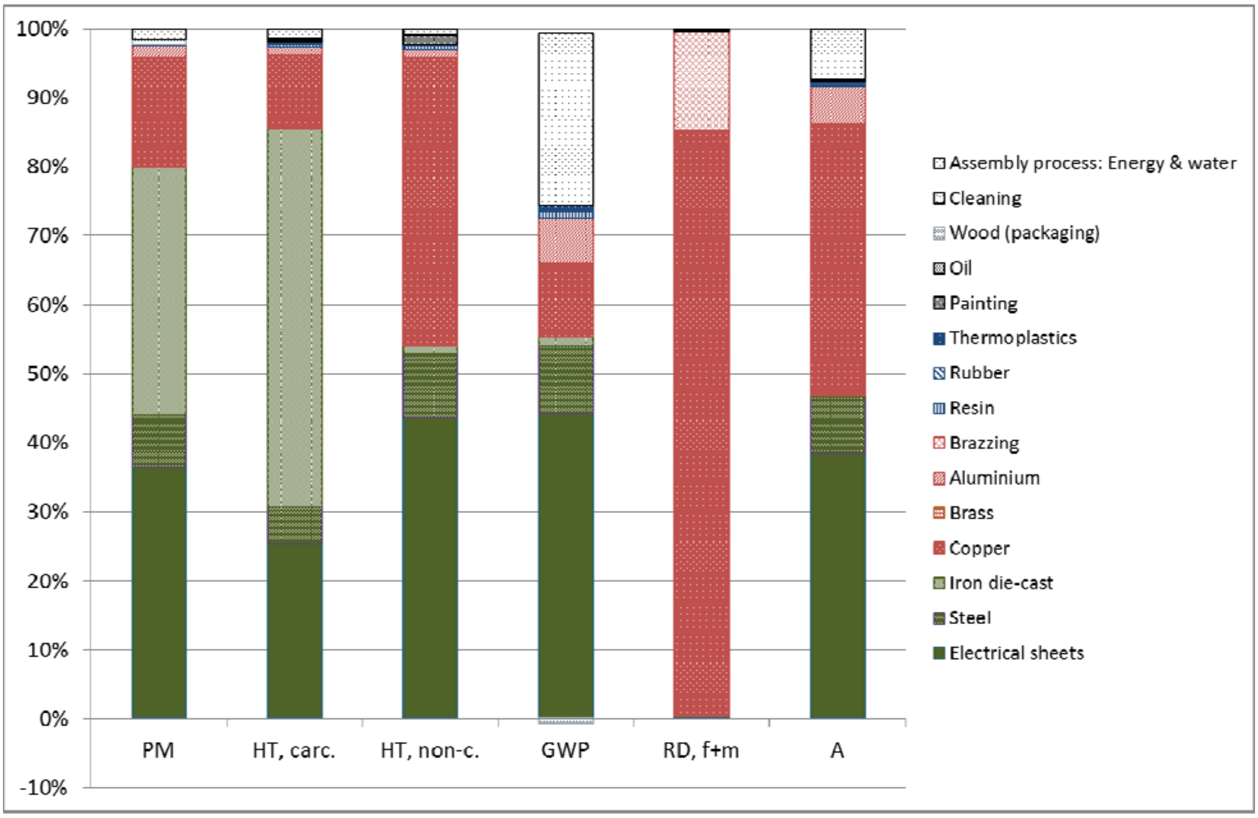


Figure 8: 100%-view of the LCIA scores of the main impact categories in PE of the IE4-motor at manufacturing stage broken down to the corresponding drivers.

Looking at this figure it can be seen that the main materials (copper, iron, steel) of the motors are also the main drivers, accounting for about 90 %, of these potential environmental impacts, besides acidification and global warming where the assembly process is also a main contributor due to its use of electricity. The materials in focus for further interpretation are the electrical sheets, steel and die-cast iron, as well as copper.

4.2 Comparative analysis of the electric motor types

Based on the results concerning the relevant impact categories and the dominance of life cycle stages, the comparative assessment of the electrical motors with different efficiency classes can be facilitated further.

To see if there are issues across the motor types, e.g. significant changes concerning the relevance of impact categories, an internal normalization in terms of “Division by Baseline” (DBB) was applied [Laurent and Hauschild, 2015], where the results of the IE2-motor provides the baseline. The results with an applied usage Scenario A) (see Table 1) are displayed in Figure 9. Here it can be seen that in that usage scenario all potential environmental impacts are reduced, and the reduction of the potential environmental impacts correlates with the increase of the efficiency classes. On average, electricity-related efficiency in the use stage is increased by about 1.2 % per efficiency class, and most of the potential impacts are then roughly reduced about 1 %. This is, however, not applicable for Human Toxicity (HT, cancer effects) where the reduction of these potential environmental impacts is lower.

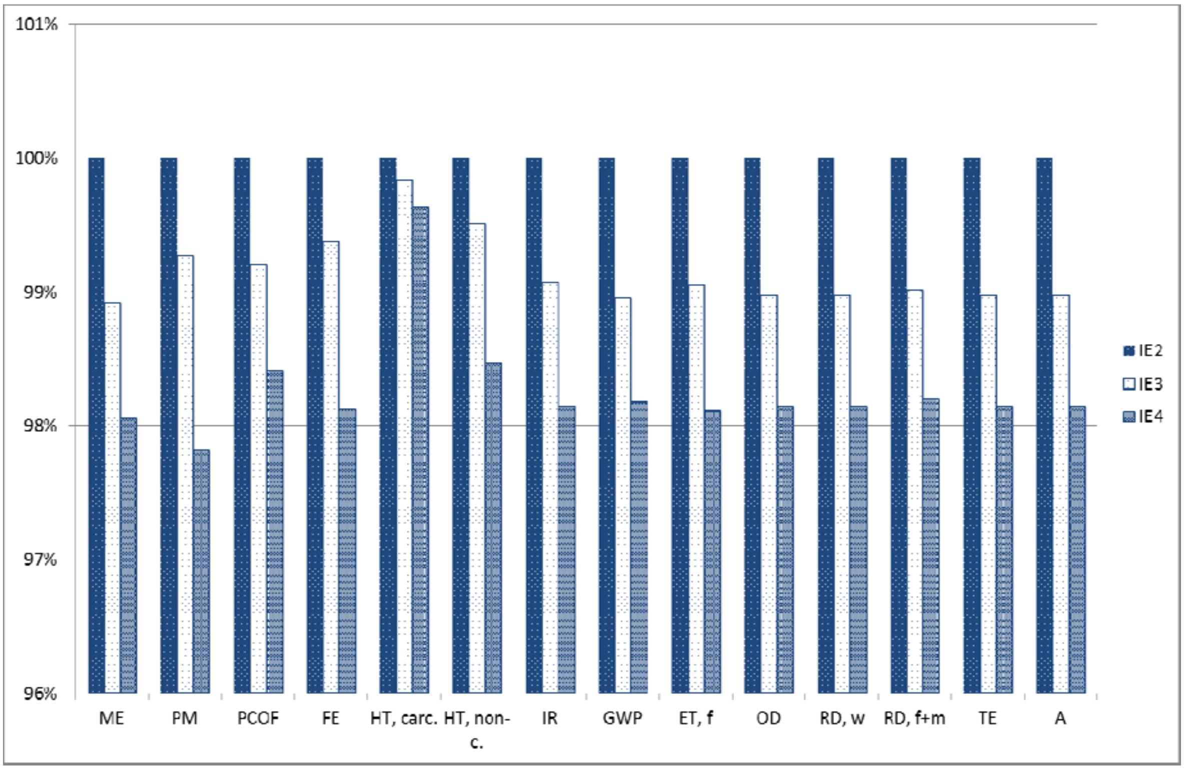


Figure 9: LCIA scores in DBB view with applied usage Scenario A).

The results of the life cycle impact assessment with the applied usage Scenario B) were evaluated accordingly, with applied internal normalization (DBB), and gave a comparable impression, besides human toxicity (cancer effects) which in this scenario even increases from IE3 to IE4. As the second difference it was recognized that the improvement of the environmental performance is even higher in all impact categories but Human Toxicity (cancer effects) in comparison to Scenario A).

According to the impact assessment, it can be summarized that the increase in the motors' efficiency reduces all environmental impacts over the complete life cycle in both usage scenarios, besides human toxicity (cancer effects).

5. Interpretation and discussion

Based on the LCIA results of the previous chapter, the LCA can now be interpreted further. For all motor types, the dominance of the use stage is obvious, even at a lower duty operation profile (Scenario B)). Based on the normalized impact scores over the whole life cycle, the most relevant impact categories are ionizing ration, water depletion and global warming potential. These categories are related to the electricity consumption during the motors' utilization and depend therefore strongly on the specific electricity mix of the region where the motors are operated. In the further, the interpretation is performed per life cycle stage:

5.1 Manufacturing and End-of-Life

Manufacturing and end-of-life stages are described together, because they strongly correlated due to the fact that the material composition of the motors is a main driver for potential impacts and benefits occurring within these life cycle stages. The increase of materials, like copper or steel in this case, in the motor's composition results in higher impacts in manufacturing, which on the other hand, in theory are compensated to some extend by material recycling and/or energy recovery at the end-of-life stage. This relation is valid for all motor types (IE2 to IE4). Allocating the potential benefit of the end-of-life stage through recycling to the manufacturing (closed loop approach) stage, the environmental impact of manufacturing is compensated by 62 % in PEs, by 52 % in GWP and by 3 % in Human Toxicity (non-cancer effects). The end-of-life stage itself was not analyzed further within the case study, since these details (e.g. different recycling scenarios) were not in the scope of the study, but it should be considered that the potential credits through recycling are quite high, but assumed to be realistic for motors of this size and weight, due to their low material complexity and high amount of valuable metals with associated, established separation and recycling processes (see also subchapter 3.3). Crucial for high recycling rates is to separate copper from iron, because copper negatively influences the recyclability or iron/steel [Alatalo et al., 2011]. This is taken into account by the disassembly of the main parts before shredding. Other end-of-life treatment scenarios, because theoretical recovery and recycling may not be always met in practice, will affect the relation between manufacturing and end-of-life stage. In other words, better recycling will compensate impacts associated with utilizing of more material more, lower recycling and/or recovery will compensate less. Looking at the normalized results of the LCIA of the manufacturing stage, the most relevant potential impacts are fossil and mineral resource depletion, human toxicity, ionizing radiation, global warming and particulate matter. The main, top 3, contributors to these impact categories were evaluated, accounting to about 90 % of impact within the respective category. The results are summarized in Table 5 for further interpretation.

Table 5: Summarized results of the life cycle impact assessment displaying the main impact categories with their main drivers for motors manufacturing.

Main Impact category	**Main drivers**
Resource Depletion, fossil + mineral	Copper, Brazing
Human toxicity, cancer effects	Electrical sheets, Iron (die-cast), Steel
Human toxicity, non-cancer effects	Electrical sheets, Steel, Copper
Acidification	Electrical sheets, Cooper, Steel
Global warming potential	Electrical sheets, Assembly process, Copper
Particulate matter	Iron (die-cast), Copper, Electrical sheets

In that context, results showed that the material selection in regard to improving the efficiency of motors is important concerning associated environmental impacts. Main contributors to the overall losses of the motor during use are losses in the functional materials copper and iron (electrical sheets), as well as in the air gaps [Volz, 2010]. So, besides optimizing the motor construction (e.g. reduction of air gap losses) within the established motor technologies, increasing the efficiency basically requires more or higher quality material which reduces these losses – even though it has to be mentioned that this is a very simplified approach, because the motor concept would have to be adapted too – and in that context copper and electrical steel are the most important material fractions [Lemmens and Deprez, 2012]. Now from an environmental point of view, the electrical sheets basically increase impacts in the ionizing radiation category, global warming potential and particulate matter categories, whereas copper dominates the impacts of resource depletion and human toxicity (cancer effects) categories. Thus, hot spots in the motors' material composition are the material fractions copper and the electrical sheets. The electrical sheets primarily because of the mass used in the motor, the copper because of the associated processes to produce the material, especially from primary sources which are needed for copper wires [Cowley and McGowan-Jackson, 2004] [EU CI, 2015]. In terms of environmentally conscious design, a practitioner now would have to valuate the corresponding impact categories to justify his choice in regard to either reducing copper losses or the losses in the electrical sheets for improving a motor's efficiency. In that context it also has to be considered that – besides the problem of valuating – in the underlying characterization methods for resource depletion as well as toxicity still are under development and bear a higher level of uncertainty compared to e.g. the impacts related to energy consumption [Huijbregts, 2001] [ILCD 2011]. For resource depletion current discussions are dominated by the search for the definition of the "right" allocation base [Schneider et al., 2015]. Whereas for toxicity assessments, three major sources of uncertainty can be named: i) Available aggregated datasets still lack certain elementary flows for a robust characterization [Huijbregts et al., 2000], then ii) fate and exposure factors do have strong correlation to the environment, like the geographical scenarios [Huijbregts et al., 2003] and then iii) the characterization itself (e.g. USEtox), is still rather young and thus under continuous development [Rosenbaum et al., 2008]. This has to be considered in any decision support context [e.g. Pennington 1999].

5.2 Use Stage

The entire use stage is a hot spot in itself, compared to the impacts associated with the other life cycle stages, where electricity consumption is the main driver for environmental impacts which are associated with the electricity generation from primary sources. Hence, the increase in efficiency of converting electric to mechanical power by the rotating electric machinery is the key to the reduction of these impacts. It has to be considered though, that the relation between the increase of efficiency and the reduction of potential environmental impact strongly depends on the applied power mix. So in case of a “green” power mix, dominated by electricity generation through renewable resources, efficiency gains in the motor will result in smaller reductions of environmental impacts, compared to power mixes relying primarily on fossil sources.

Looking at the efficiency of the motors (Table 4) it can be seen too, that the efficiency at the OP2 is higher than in OP1, which is currently regulated by the implementing measure on motors within the framework of the ErP directive. Therefore it can be argued – depending on the operating profile – whether the increase of the efficiency classes is the key to the “right” choice of the motor. Rather, it might make sense to utilize a more powerful, i.e. oversized, motor, which then runs at OP2 most of the time, instead using a higher efficient less powerful, i.e. right-sized, motor which correspondingly runs at OP1 for most of the time. This is also the explanation to the higher increase of environmental performance with the increased efficiency in usage Scenario B), since there the motors run with a high share at OP2 (see Table 3). In this context it has to be mentioned that this does not apply to all motor technologies, as for instance synchronous motors do not have this behavior since their efficiency is more or less the same for all operating points.

5.3 Comparative Assessment

The comparative life cycle assessment clearly indicated that any increase in efficiency is environmentally preferable with the applied usage scenarios (assumed 20 years of operational life) and current technological set-up for electricity generation. After external normalization and weighting of results, the study clearly indicated the benefits of an improved efficiency in terms of reduced impacts, even when applying a lower duty operating profile (Scenario B)). The extra effort when building a more efficient motor in manufacturing stage, due to the use of more material, as well as distribution, because of the higher weight, is compensated by higher credit at the end-of-life stage, as well as the savings when using the product. In this regard the pay-off between higher impacts in manufacturing and to the lower impacts in usage for the increased efficiency was calculated to about a month in terms of PE, and only to 8 days in GWP as a representative for the assessed impact categories, related to electricity consumption. The exchange of an IE2 motor with an IE4 motor reduces CO_2-emissions by about 80.000 kg CO_2 eq. (4160 kg CO2 eq. per year) in Scenario B) and by 145.000 kg CO_2 eq. (7240 kg CO_2 eq. per year) in Scenario A). The data for the comparison of the IE2 with IE4 motor, i.e. the days of operation after which additional efforts in materials, manufacturing and distribution are compensated by savings in the use stage, as well as potential credits from end-of-life, is summarized for PE, GWP, HTc and RD in Figure 10. In this context an additional scenario was added, to check how a different, worse in terms of recycling/recovery rates, approach would influence the break-even in environmental impacts. Therefore only 50 % of the potential credits from the end-of-life stage were accounted to the motor system.

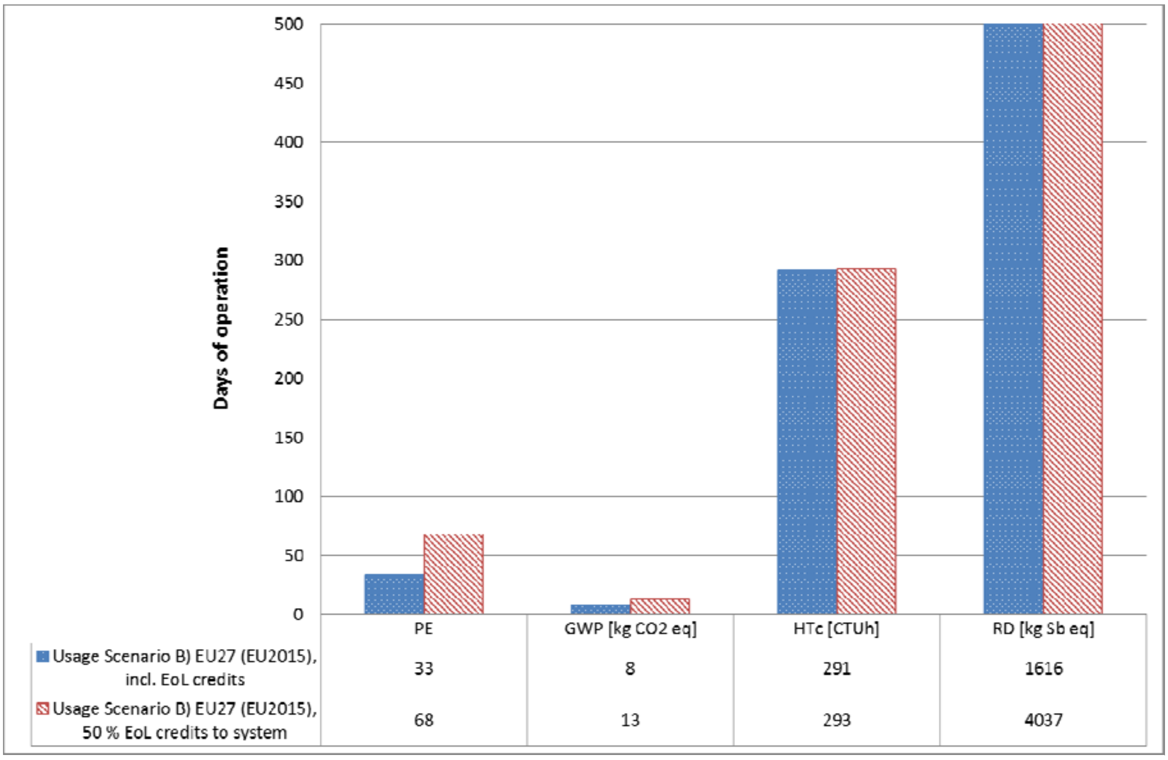


Figure 10: Graphic display of the break-even calculation for the exchange of an IE2-motor with an IE4-Motor in days of operation. It shows after how many days of operation the additional effort in material, manufacturing and distribution is compensated by savings in usage and credits for EoL.

Based on this data it can be seen that the additional effort for increasing the motors’ efficiency corresponds in terms of GWP to an additional impact of 204 kg CO_2 eq, credits from end-of-life account for 116 kg, leaving net 88 kg CO_2 eq to be compensated at the use stage. Comparing this to the figures mentioned above, it’s clear that this compensated quickly. With lower recovery and recycling rates, the time period needed for break-even is extended, especially regarding the resource depletion (fossil, metals) indicator.

By applying an internal normalization by the means of DBB the impact categories’ performance could be assessed individually in between the motors with different efficiency classes. An increase of (Scenario B)) or a lower reduction of potential environmental impacts (Scenario A)) with increase of efficiency could be observed for human toxicity (cancer effects). This is caused by the higher utilization of copper material with the increase of the efficiency class. Since there are not enough savings in that category in the use stage, the total score over the whole life cycle increases with the applied use stage Scenario B). Looking deeper into this issue, the break even for this impact category would be reached, when exchanging a IE2 motor with a IE4 motor, after about 15 years in Scenario A) and after about 27 years in Scenario B). This should be considered in ecodesign decision support context with caution due to the issue of uncertainty of this impact category, as discussed previously. More generally this fact can be seen as an indication that there could be cases were this wouldn’t be true (e.g. other usage scenarios with different load-time profile and/or shorter reference life time) or that when further increasing efficiency it can lead to higher impacts in certain impact categories, as toxicity impacts in this case. Now to further check the robustness of the obtained results, these points were addressed in the sensitivity analysis in the following section.

6 Data quality and sensitivity analysis

To validate the LCIA results as discussed in the previous section, uncertainties and data quality in terms of representativeness and appropriateness have to be depicted as basis for the further sensitivity analysis and scenarios, which then lead to the final conclusions in chapter 7.

6.1 Representativeness and appropriateness of LCI data

The representativeness and appropriateness of the LCI data is now discussed per life cycle stage.

Manufacturing stage

Relevant data for modelling the manufacturing stage of the motors for that study are the supplied bill of material and energy consumption in the assembly process. The bill of material and weights were taken directly out of the engineering tool and can be rated of very good quality. Treatment of the materials and manufacturing steps of the parts are reflected by the aggregated generic data sets of materials or processes, supplied by thinkstep, and can be rated of good quality. The assembly process energy allocated by working hours is known to include a high level of uncertainty, as already mentioned in the goal & scope, but due to the dominance of the impacts associated with the materials themselves the importance can be rated rather low and the current approach can be rated as worst case scenario. As laid out above copper and the electrical sheets do have the highest influence, therefore these should be addressed by a sensitivity analysis to evaluate the limits of the discussed results in context to the decision support.

Use stage

Data relevant for modelling (losses of the motors at the corresponding operating points) was taken from SinaSave [SinaSave 2016] and is based on the products technical documentations. Underlying test and calculation methods are standardized and applied in policy context. Therefore it can be rated as of very good quality. The applied use stage scenarios can be rated as representative, but it has to be considered that the application range of asynchronous motors is quite divers and results in different scenarios might vary. Especially in context it shall be mentioned that besides the operating profile, the operational life and the operating hours per years have a strong influence on the impacts related to the use of the motor. Both parameters correlated to the nominal power of the motors [Almeida et al., 2008]. Additionally to that it should be considered that the impacts from electricity generation are decreasing through the increased contribution from renewable sources, especially wind power, as it is documented for instance for the European Union [Agora 2016]. This potential future energy scenario could affect the interpretation of the comparative assessment and hence should be addressed in a sensitivity check.

End-of-life stage

The end-of-life treatment process itself can be described as representative for the current state of the art of motor recycling in industrialized regions like Europe. Additional scenarios could be applied considering lower recycling and recovery rates, that would be applicable in other regions; or to analyze for instance the effect of the reuse of certain parts of the motor, reflecting current initiatives in Europe, as the circular economy package [EC 2015a] and standardization activities regarding material efficiency [EC 2015b]. For this case study, this context is rated as of minor significance, since the evaluation of environmental break-even in subchapter 5.3 showed that even when not crediting manufacturing with the benefits from the end-of-life stage, the additional impacts in manufacturing in terms of PE are compensated in use stage, low duty Scenario B), in less than 4 months.

6.2 Sensitivity analysis

As outlined in the previous section, copper and electrical sheets play a major role concerning the environmental impacts of the motors, especially in the comparative assessment when assessing the trade-offs between the life cycle stages when the efficiency of the motors is increased. Thus in the first part of the sensitivity check different datasets for copper as well as the electrical sheets were used. Additionally concerning the relevance as well as ongoing discussion around the limits of the assessment of the resource depletion impact category, the results were checked by applying a different characterization model. Then the third check was performed by applying a potential EU2030, as well as EU2050, power generation scenario reflecting the developments in the EU concerning electricity provision.

Robustness of the result against different materials background data

In the study copper and the electrical sheets were identified as one of the drivers of the environmental impacts, especially in the manufacturing stage (and correlating in the end-of-life-stage), therefore a sensitivity check using different background data sets for these materials was performed concerning the robustness of the results and interpretation. Copper in the motor is used in the form of wires and has some influence on the efficiency of the motor as a reduction of the electrical losses in copper is one lever for increasing the motor's efficiency. For these wires only primary copper from electrolysis can be used. In the initial assessment a dataset for copper (electrolysis, 99,9999…%) in global context was used, since the complete supply chain is – in a general context – unknown or not further specified. Additionally available in the database was a corresponding dataset for copper wires in a European context supplied by the Copper Institute from 2012, which also seems to be applicable in the study. This dataset was then picked in terms of checking the results of the study. Figure 11 shows the externally normalized LCIA score of the IE4 motor's manufacturing stage with the two applied LCI datasets Cu(GLO) by thinkstep and the Cu(EU15) by the Copper Institute in comparison to visualize the differences.

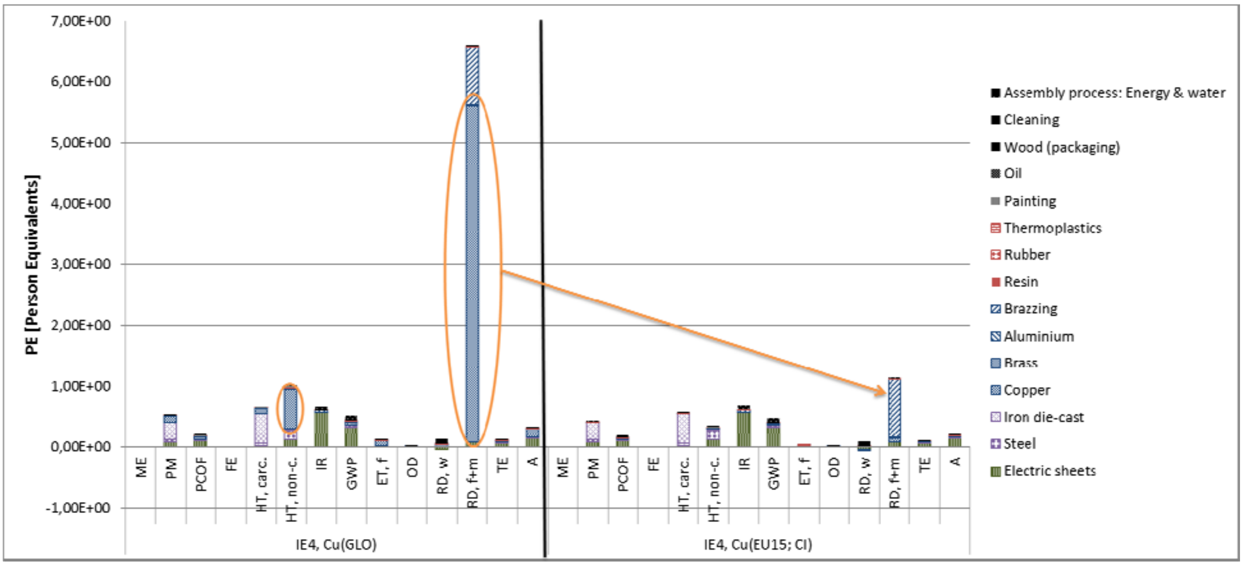


Figure 11: Normalized LCIA scores in PE of the manufacturing stage of the IE4 motor with the two different LCI datasets Cu(GLO) by Thinkstep and Cu(EU15) by the European Copper Institute.

The figure shows clearly the issue of the LCI dataset choice in regard to the interpretation of the LCIA results. So when picking the European Copper Institutes Cu(EU15) dataset, copper isn't a driver in regards to resource depletion and Human Toxicity (cancer effects) anymore and both impact categories' importance is reduced in that context. To put that into the context of the comparative assessment, again internal normalization by DBB was applied to the LCIA results over the whole life cycle, but there were only minor changes of the results, in the respective categories human toxicity and resource depletion, hence the overall interpretation stays valid.

Explanation to that lower rating could be outdated LCI data and/or missing elementary flows for proper characterization; or on the other hand more accurate data compared to worst case approximations due to lacks of detailed data. Looking at their issuing dates, option one seems more reasonable, since the European Copper Institute's free, association data set is from 2010, whereas thinkstep continuously maintains their purchasable background datasets [GaBi, 2016]. This has been verified by directly comparing the two datasets elementary flows and the EU15 copper dataset basically shouldn't be applied anymore.

The electric sheets were modelled with an aggregated dataset for the cold rolled steel coil by thinkstep, based on the fact that iron is the main component to both, assuming a standard cold-rolled non grain oriented electrical steel with 1-3 % of Silicon added used in the motors in the initial set-up of the assessment. In terms of a sensitivity check we used a dataset provided by a supplier of this electrical sheet material, thyssenkrupp Steel, assuming a better fit to reality and a higher degree of accuracy. Figure 12 displays the results for the IE4 motor respectively for all motor types in comparison to the initial assessment of the manufacturing stage.

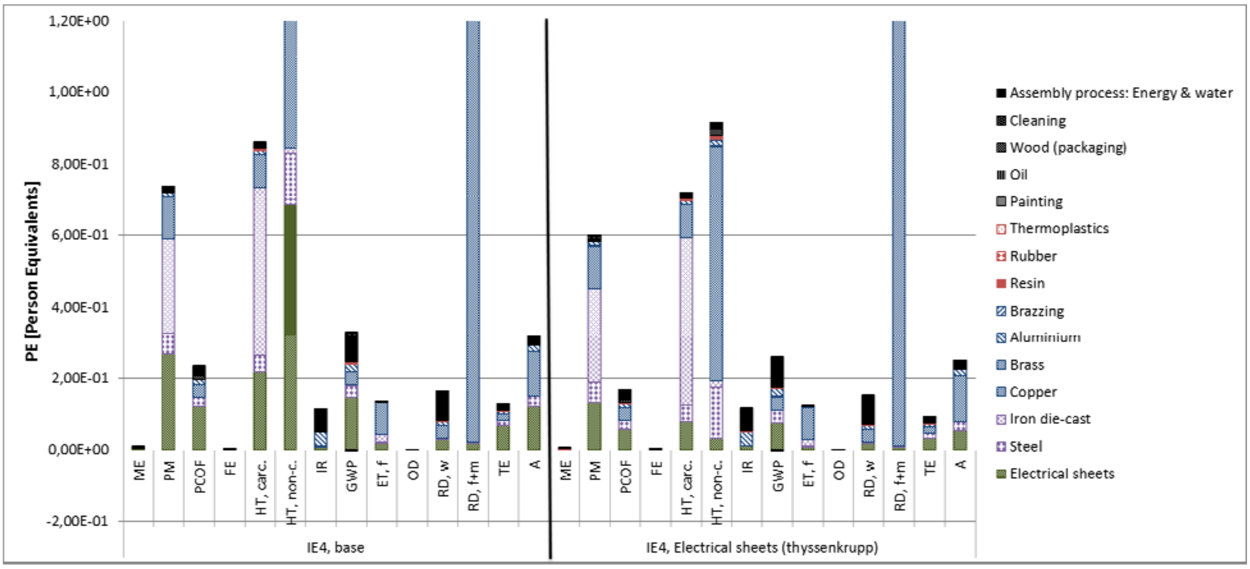


Figure 12: Normalized LCIA scores in PE of the manufacturing stage of the IE4 motor with the two different LCI datasets for steel by thinkstep and by thyssenkrupp Steel. The vertical axis is cut at 1.2 PE to have a better look at the changes of the impact categories besides resource depletion, which is dominated by copper and its course is known.

It can be seen that in all impact categories, where the electrical sheets have a significant contribution to the scores have changed, in all impact categories the electrical sheets contribution is lower with the more accurate dataset. Especially human toxicity decreases significantly, whereas for the others the reduction is more or less comparable. To put these differences into the context of the comparative assessment of the motors with different efficiency classes, DBB was applied again to the LCIA scores of the whole life cycle.

Comparing these results with the initial assessment, again minor changes can be observed in regard to human toxicity where there’s now a minor decrease instead of a minor increase as in the initial assessment. In context to toxicity impact assessment methods, this change can be regarded as insignificant, hence the interpretation as laid out in the previous chapter remains valid. Or to put it in other words, decision support should still be carried out carefully when based on these results in the toxicity category. This can generally be accounted to the fact that the use stage is dominant and significant changes in the LCIA scores of manufacturing stage become insignificant over the whole life cycle with the applied usage scenarios.

EU2030/2050 scenarios for electricity production

To check the obtained results, which predominantly are influenced by the impacts related to electricity generation, two additional scenarios were derived based on a publication of the German VDMA's group for power systems. Background of the scenarios is the increase of renewable energy sources, like wind and solar, for electricity generation. Therefore the available EU27 power mix by thinkstep was modified according to the figures in Table 6. The EU2030 scenario was derived based on the figures of the above mentioned report, whereas the EU2050 is an own assumption of a potential further development of the electricity generation.

Table 6: Parameters of EU2030/50 power mixes in percentage of the total contribution per energy source.

	EU2030 (Source: VDMA power systems [VDMA, 2010])	EU2050 (own projection)
Energy Source	Contribution [%]	Contribution [%]
Biogas	4	8
Biomass solid	4	4
Coal gases	0	0
Hard coal	6.5	2.5
HFO (Oil)	2.5	2.5
Hydro	12	14
Lignite	7	3
Natural gas	16	12
Nuclear	19	15
Photovoltaics	5	8

Wind	23	30
WtE	1	1
Additional parameters		
Grid losses	4.35	4.35
Own consumption	1.39	1.39

Figure 13 now displays the results of the life cycle impact assessment of Usage Scenario B) applying a EU27 grid mix (EU2015) adapted with the parameters of Table 6.

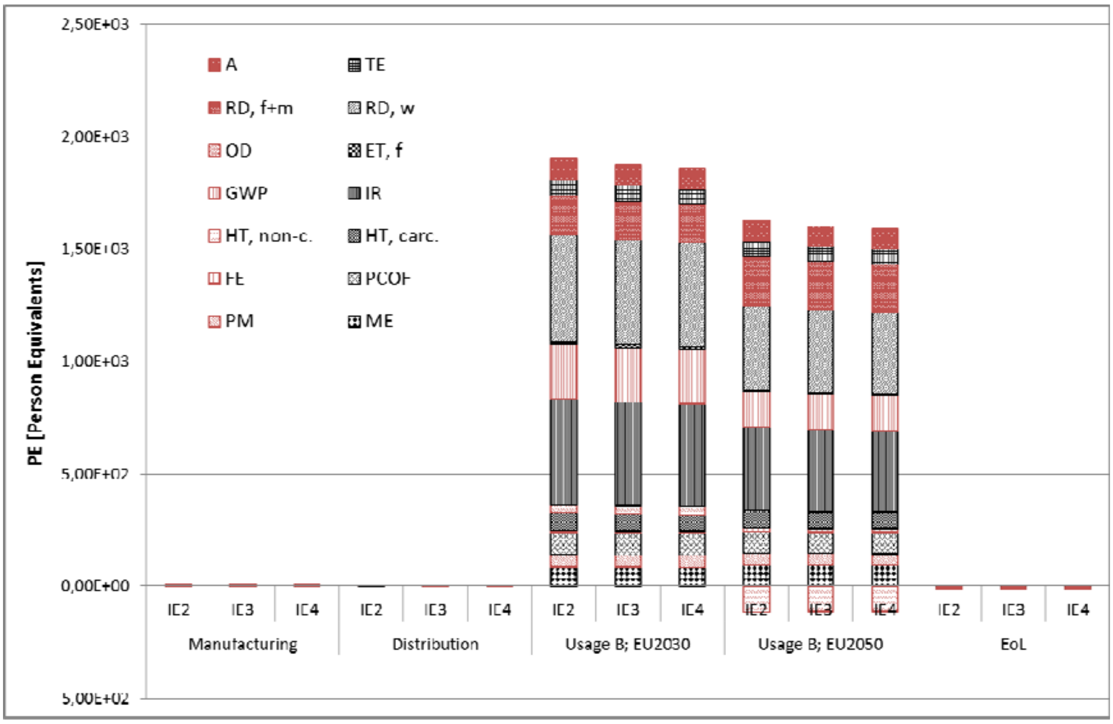
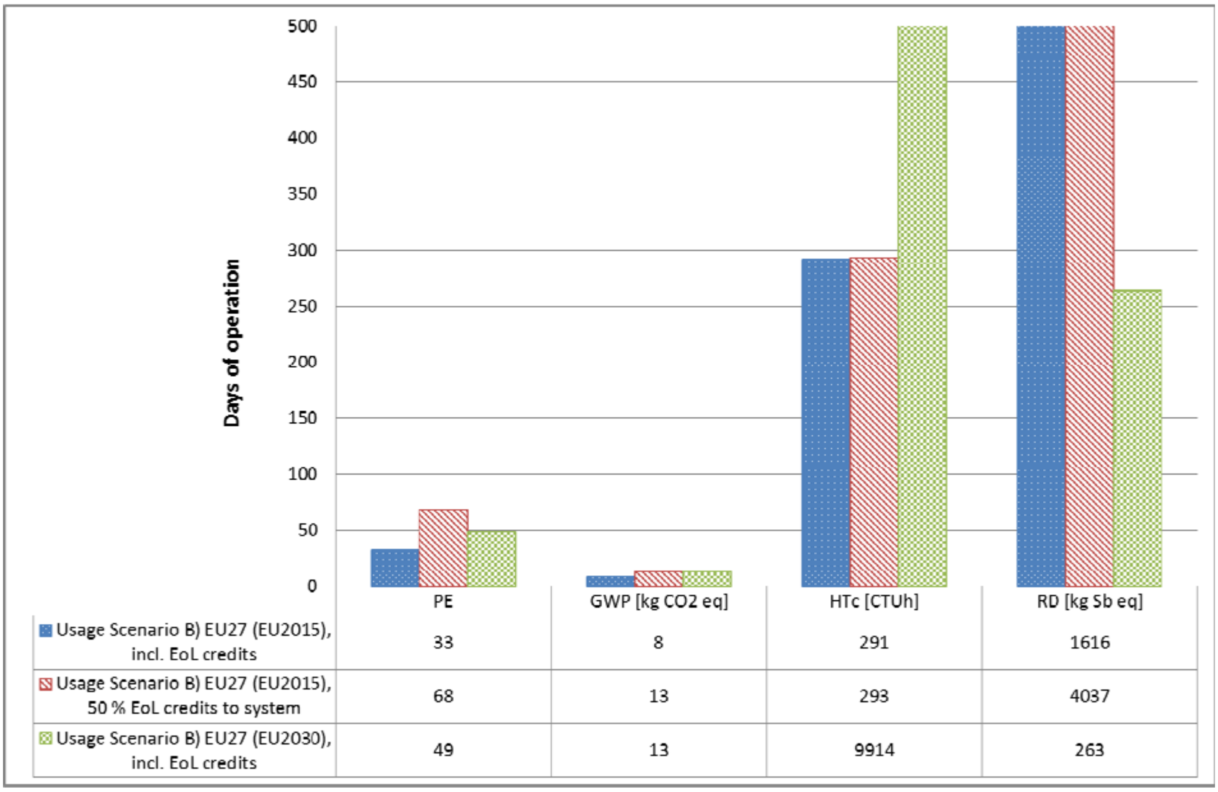


Figure 13: Normalized LCIA scores of motors with different efficiency classes in different electricity generation scenarios using the usage Scenario B). Details to the scenarios are provided in Table 6.

The results show that there’s a significant reduction of the impacts associated with the electricity consumption through the increased contribution of renewable energy sources, but – even for the EU2050 projection – the impacts associated with the manufacturing stage, as well as distribution and EoL stages, are still several orders of magnitude lower than those associated with the usage stage. Hence even up to 2050 improving efficiency will be an important point in the EU to reduce environmental impacts driven by electricity consumption.

For the further analysis the environmental break-even for the exchange of an IE2 with an IE4 motor was calculated for the most relevant impacts by dividing the additional impacts of the motor with the higher efficiency at the materials, manufacturing, distribution and end-of-life stage through the savings in the use stage for the study's base case. This is shown in Figure 14 in comparison with the results from 5.3.



	PE	GWP [kg CO2 eq]	HTc [CTUh]	RD [kg Sb eq]
■ Usage Scenario B) EU27 (EU2015), incl. EoL credits	33	8	291	1616
▨ Usage Scenario B) EU27 (EU2015), 50 % EoL credits to system	68	13	293	4037
▩ Usage Scenario B) EU27 (EU2030), incl. EoL credits	49	13	9914	263

Figure 14: Environmental break-even calculation in days of operation, in normalized (PE) scores and in absolute figures in 3 different impact categories

According to this calculation it can be stated that through the increased contribution of renewable energy sources to the electricity generation, the break-even in PE, GWP and RD is achieved after a longer time period. Especially for HT (cancer effects) the increase in days of operation is high and is then exceeding the assumed service life. Interestingly there's a significant reduction of time period needed for the break-even in resource depletion, compared with the base case. This could be a topic of the characterization method and the allocation of impacts from resource consumption of electricity generation by renewable energy sources. Savings from increased energy efficiency in operation seem to be accounted for even higher than from non-renewables. In PE and GWP the time period for the break-even increases when more of the electricity is generated from renewable sources.

7 Conclusions and further work

The normalized and weighted results of the comparative life cycle assessment case study on electric motors with different efficiency classes led to the conclusion that in the current technological set-up, especially concerning electricity generation and potential scenarios with higher contribution from renewable resources, any improvement in efficiency in the motor’s operation is environmentally beneficial, at least within the range of the usage scenarios applied in this study. This means that the trade-off between the life cycle stages is beneficial over the whole life cycle. Drilling this further down to the individual impact categories, a special behavior was observed for human toxicity (cancer effects), where the break-even between the additional effort for improving efficiency and the savings at use could only be reached after the assumed service life of the motor when more electricity is provided by renewable resources. Therefore managing this aspect will require special attention, especially considering the uncertainties and discussions underlying the available impact assessment methods, and decisions in ecodesign context should be taken carefully. This means that further research activities should tackle the aspect of the robustness of the characterization models for toxicity to enhance their applicability in decision support context. The same might apply for the resource depletion indicator which in the current guidance for PEF pilots is an aggregated category covering mineral, metal and fossil resources. The use of more mineral and/or metal resources therefore can be compensated by savings of fossil resources like in this case study. This may lead decision makers in the wrong direction, especially when both: energy related impacts as well as the resource depletion of minerals and metals need to be managed. End-of-life treatment scenarios also have a high influence on this characterized impact through the crediting of the system under study with the benefits. This indicates that political initiatives as well as legislatives acts tackling these issues have to bear that in mind or rather should improve the assessment methods before deciding and starting these initiatives to avoid burden shifting or a general dilemma.

For today's motor producers or rather LCA practitioners in industry, same applies when using LCA as a tool for decision support. The externally normalized results of the study indicate that future developments should still tackle the aspect of further improving efficiency, because in the current (and prospective) technological set-up for electricity generation, any reduction of consumption decreases environmental impacts. On the other hand the internally normalized results indicate a burden shifting between energy related impacts and toxicity impacts (and maybe to resource depletion if assessed individually for fossil and metal resources). Thinking this through it can be concluded that decision making supported by LCA is still very difficult because of the uncertainties through immature impact assessment and characterization models, generic secondary data and the lack of proper external normalization factors, reflecting the carrying capacity of the ecosystems and political consensus on the weighting of the individual impact categories.

The study also showed the relevance of the load-time profile, indicated by the comparison between the two usage scenarios, and the motor's service life. Generally, the motors' efficiency is higher in a partial-load condition around 75 % of nominal power compared to the efficiency at 100% load. Hence, it would be crucial to evaluate the environmental performance of a motor or rather a drive system optimized in context to the specific characteristics of the application scenario in comparison to gains achieved by the optimization of single components. Another point in that context is generalization of the results of the study to other motor sizes (nominal power). Efficiency gains of motors with smaller nominal power, e.g. 11 kW, will be lower in absolute numbers, as well as the assumed service life be shorter (10-15 years), this could then lead to different results concerning the trade-offs or rather the environmental break-even of these impacts.

So when finally concluding on the deep dive into the trade-offs between life cycle stages in ecodesign context, it can be stated that these two aspects could be in the scope of further work to complete the picture of a relevant product category in an energy and material efficiency context.

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