Approach to Assess the Impacts of Circular Economy Measures: Case Study of Electric Motors in the EU

Master Thesis
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List of Abbreviations

AC	Alternating Current
BOM	Bill of Materials
CE	Circular Economy
CEAP	Circular Economy Action Plan
CFF	Circular Footprint Formula
CRM	Critical Raw Materials
DC	Direct Current
EC	European Commission
EF	Environmental Footprint
EOL	End-of-Life
ESPR	Ecodesign for Sustainable Products Regulation
EU	European Union
GHG	Greenhouse Gas
GWP	Global Warming Potential
ILCD	International Life Cycle Data System
JRC	Joint Research Centre
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
MEErP	Methodology for Ecodesign of Energy-related Products
MEPS	Minimum Energy Performance Standard
OEMs	Original Equipment Manufacturers
PEFCRs	Product Environmental Footprint Category Rules
POP	Persistent Organic Pollutants
PAHs	Polycyclic Aromatic Hydrocarbons
PM	Particulate Matter
PV	Photovoltaic
RBR	Recyclability Benefit Rate
VOC	Volatile Organic Compounds
VSD	Variable Speed Drive

1. Introduction

1.1. Motivation

The European Union’s (EU) long-term climate goal is to be climate neutral by 2050 with a net-zero economy [1]. A brief look at the statistics [2] for final energy consumption in the EU in 2020 reveals that petroleum products accounted for the highest share (35%) and electricity ranked second (23%). The main energy source for electricity was renewable energy (39%), making the electrical power sector one of the fastest sectors to decarbonise [2].

Electricity plays a major role in decarbonisation as renewable energy sources such as hydropower, photovoltaic and wind power can generate carbon-free electricity. As the share of electricity in energy end-use increases, the share of electric motors systems will grow as they have many applications in industry sectors, not to mention their potential to decrease emissions in the transport and household sectors as well, through electric vehicles and heat pumps [3].

Prior to the predicted future market growth which will lead to electric motors consuming more electricity, they already account for the largest single electrical end-use. They are estimated to be responsible for approximately 45% of electricity consumption globally and their global carbon emissions are expected to rise to 8570 Mt per year by 2030 [4]. According to the Electrical Motor Market Report [5] as quoted by Tiwari et. al. [6], the electric motor market is expected to have an annual growth rate of 6.9% and it is estimated to reach USD 169 billion by 2026. In the EU, about 8 billion electric motors are in operation and they consume approximately 50% of the electricity that the EU produces [7]. Resource efficiency is gaining momentum in the EU alongside the circular economy action plan (CEAP) announced due to high energy consumption and emissions linked to materials and production processes, not to mention that the EU also has a raw material import dependency with high economic risks. It is also to note that magnets in motors are primarily made with rare earth materials due to their natural magnetic properties. Hence, the energy and resource efficiency of the electric motors is set to be a vital factor for EU climate targets, where the simple performance or material requirements for efficiency improvement in the Ecodesign implementing measure can bring forth huge saving potentials just through the sheer numbers of electric motors [3].

The current Ecodesign Framework aims to regulate energy efficiency and other environmental performance of energy-related products in the EU [8]. There are Ecodesign requirements that apply to electric motors and variable speed drives (VSD). The requirements entered into force in 2009 and were revised in 2019, and the latest requirements of the 2019 regulation will enter into force in July 2023 [9]. The Methodology for Ecodesign of Energy-related Products (MEErP) is the standardised methodology used in the preparatory study to establish new regulations [10]. However, the resource and material efficiency aspects were less of a focus in the modelling of the MEErP in the past. Consequently, the current version of the MEErP and the EcoReport tool, a simplified life-cycle based tool for ecological assessment based on the bill of materials which is finalized in 2013, is presently undergoing a review and getting an update to ensure they fit the purpose of the current affairs and are in line with the current development of policies [11, 12].

1.2. Research Question

The goal of the study is to assess the impacts of circular economy (CE) measures with a case study of electric motors in the EU. The main research question is divided into three research sub-questions.

Main research question: “*How to identify circular economy measures for product policies and assess their environmental impacts for the case study of electric motors in the EU?*”

The energy consumption in the use phase is currently the main contributor to environmental impacts for electric motors [13]. However, as industries are moving towards renewable energy, it is expected that energy use and emissions during the use phase of electric motors will have less impact. Instead of focussing on energy efficiency, this study aims to improve the environmental impacts of electric motors in the EU by implementing circular economy measures. For example, by extending the lifetime for certain parts of electric motors, identifying crucial phases other than the use phase, optimizing resource use and other material efficiency aspects.

Research sub-question 1: *How to identify circular economy measures that have high saving potential with different tools?*
With the review of the MEErP, the EcoReport tool is being revised and hence it is deemed interesting to compare the impact assessment results of both EcoReport tools. Throughout the study, the old version of the EcoReport tool will be referred to as the "current EcoReport tool" and the new version the "revised EcoReport tool" to be in line with the draft report by the Joint Research Centre (JRC) for the Review of the MEErP [14]. It is to note that the "revised EcoReport tool" is currently still under revision and not finalized yet. The focus here will be to determine if the current and revised EcoReport tool is robust enough to identify the main hotspots other than the energy consumption in the use phase. The impact assessments result will be compared and possible circular measures as improvement options or ways to reduce environmental impacts will be conceptualised from the hotspots.

Research sub-question 2: *How to assess the impacts of circular economy measures on an individual product level?*
Circular economy measures on a product level will be identified based on the results of the impact assessment. Several applicable measures will be selected, and the impact of the selected measures will be evaluated. It is important to note that the focus here will not be on choosing and selecting the best measure based on the best available technology for electric motors but to determine if plausible circular economy measures can be identified from the impact assessment results obtained from the EcoReport tool. The selected circular economy measures will be categorised according to a taxonomy adopted for Ecodesign implementing measures based on the 3R framework [15].

Research sub-question 3: *How to assess the long-term impacts of circular economy measures based on sub-question 2 on the EU market?*
To assess if the circular measures on a product level are suitable to be implemented as a policy, the modelling and analysis of scenarios will be carried out. The scenarios will be modelled based on the circular economy measures selected for electric motors in the second research question. The impacts of the measures will be examined through upscaling of scenarios on the EU market and medium-term stock modelling approach for the EU coupled with the individual product's environmental impact over longer time periods.

1.3. Research Approach

The research approach is broken down into three phases. In the first phase, the environmental impact results from the current and revised EcoReport tools are examined. Circular economy measure recommendations and conclusions are then drawn from the impact assessment results and hotspots.

In the second phase, implementable circular economy measures are identified. A focus is placed on the 3R framework, and to that end, measures that can be categorised under the three circular economy strategies reduce, reuse, and recycle. When identifying circular economy measures, the emphasis is put on life cycle phases from the EcoReport tool such as raw materials, maintenance, and repair, and EOL. For example, if the EOL phase has the highest environmental impact due to disposal at landfills, measures such as increasing the collection rate of electronic motors may be implemented. If raw materials extraction is the hotspot, measures such as increasing recycled content or recycling target may be implemented. It is to note that circular economy measures for the use phase will not be examined as its primary input is energy consumption. The identified circular economy measures will then be evaluated to identify the most effective measures.

In the third phase, with a quantitative scenario modelling and analysis over a longer period, the selected circular economy measures can be further evaluated through the calculation of environmental benefits, implications, materials import dependencies and so on.

Figure 1 outlines the overall thesis structure. The results are expected to contribute to the revision of the EcoReport tool and indicate relevant efficiency improvements in Ecodesign regulations for electric motors.

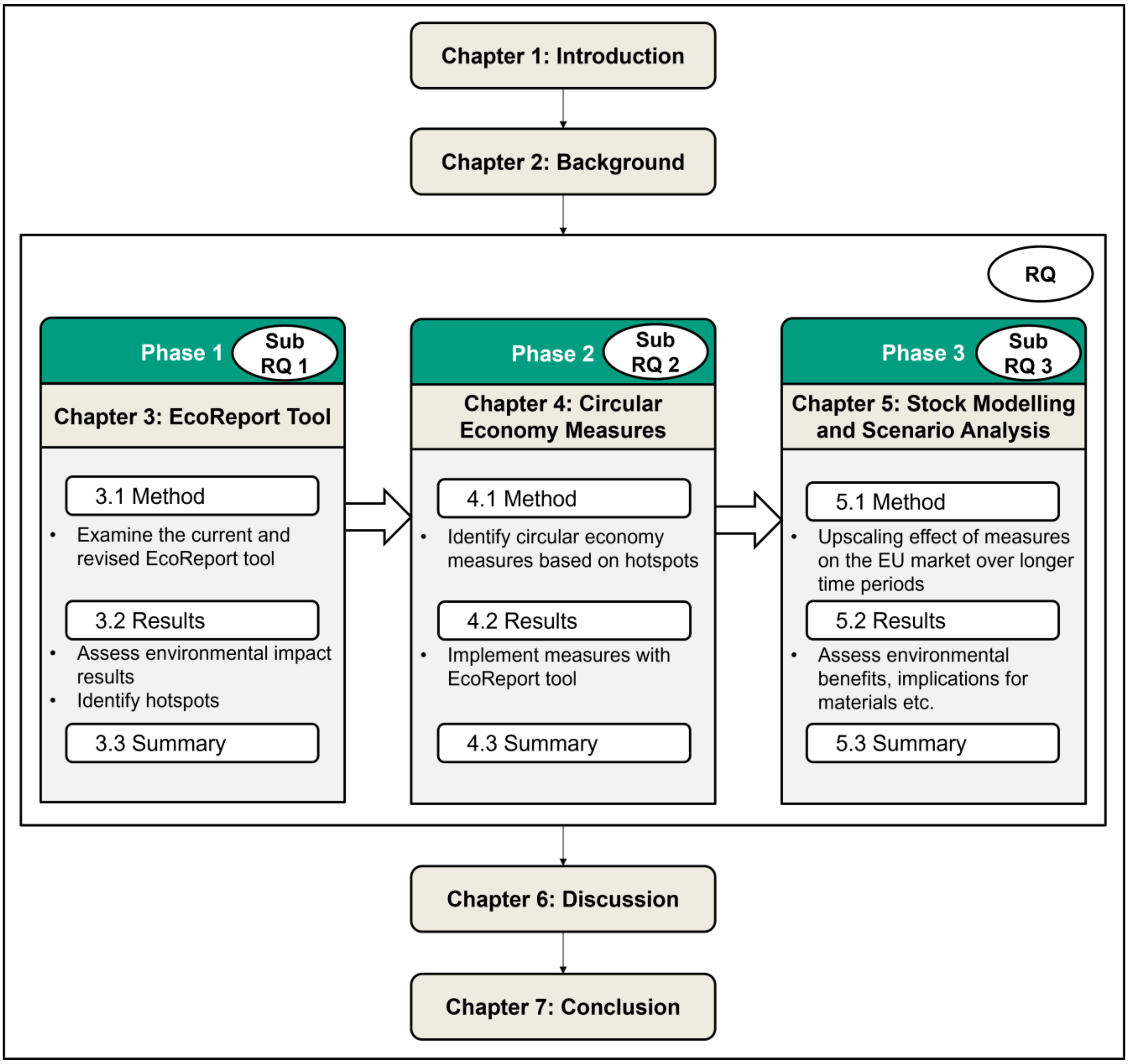

Figure 1: Overall thesis structure

2. Background

2.1. Electric Motors and Active Environmental Impact Regulations

Electric motors are devices that convert electrical energy to mechanical energy in the form of rotation. A VSD is an electrical device used to control the speed and torque of an electric motor by varying the frequency and voltage applied depending on the application requirement [7].

As stated in the Ecodesign Preparatory Study on Lot 11 Motors [13], motors are categorized into two types, direct current (DC) motors and alternating current (AC) motors. According to the report, AC (or induction) motors dominate the EU market as they offer more precise and reliable control of rotation in comparison to shunt wound motors, the dominating motors in the DC motors market. Depending on the different motor types, the percentage of sales in the market varies. The unit market share for AC motors is about 24 times larger than DC motors, and the market trend for DC motors is showing a decrease, except for brushless permanent magnet DC motors which are highly efficient but are also costly and contain various critical raw materials (CRM). The performance standards and regulations are hence focused on the dominating technology, which is the low-voltage induction motor. [13]

The environmental impact of electric motors and VSDs mainly stems from energy consumption during the use phase [13]. It is reported [16] that when looking at a VSD alone, it has significantly less environmental impact than a motor as it is highly efficient at mid to high load and because only some motor systems have VSD. Since the sales of VSDs are expected to increase, it was recommended to have more requirements set out in regulations for them. The Ecodesign requirements published in 2019 for electric motors and VSD included requirements for VSDs, which were in force since July 2021.

The Ecodesign regulations and requirements on electric motors are focused on energy efficiency as the use phase has the highest environmental impact contribution, but further energy efficiency improvements are technically rather limited (see Figure 2) and their contribution in reducing the environmental impact will be minor. In light of the growing focus on the circular economy, the end-of-life (EOL) phase of electric motors is expected to become increasingly significant in the future. This will not only have environmental implications but also pose a resource access challenge for the production of new motors. Currently, there are no active requirements for the EOL phase.

A study in the United Kingdom from 2021 [6] revealed that the recycling of electric motors is the most researched EOL strategy while remanufacturing, reusing and repairing are less looked into. According to the study, even though electric motors consist of materials that are highly recyclable and have high economic values, components such as copper wire windings are difficult to be removed cleanly from the motor because of their complex structure and unwanted materials will affect the quality of the recycled copper. EU recycling targets are also often based on the total mass percentage of the material and CRM may not be suitably recycled this way due to their low weight fraction. The remanufacturing, reusing, and repairing of electric motors are costly and inefficient due to the complex disassembly process and lack of information about the condition of the returned product. The survey also revealed that repair strategies for electrical machine components are not popular amongst companies. It is suggested that a proper methodology for disassembly and inspection, such as the integration of industry 4.0 technologies and the digital product passport should be further investigated [6]. The environmental impact of digital technologies on electric motors' potential efficiency improvements and rebound effects will also be interesting prospects to look into, but this discussion falls outside of the scope of this study.

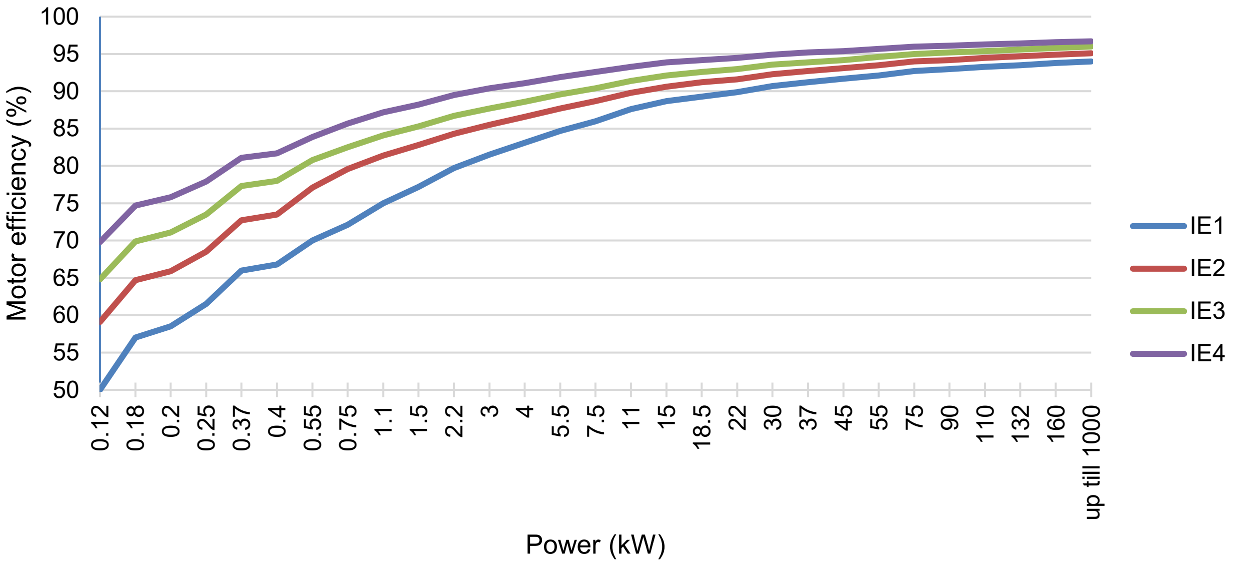

Figure 2: Efficiency class of motor with power range up to 1000 kW, classification according to IEC 60034-30 [9, 13]

Regulation No. 640/2009 [17] with regard to Ecodesign requirements for electric motors and VSDs was first introduced in July 2009. The minimum efficiency requirements for 2-, 4- and 6-pole, single-speed, three-phase, induction motors in the mentioned power range were applied in different phases.

1. From 16 June 2011, motors with a rated output of 0.75 – 375 kW must meet the IE2[1] efficiency level.
2. From 1 January 2015, motors with a rated output of 7.5 – 375 kW must meet the IE3 efficiency level or meet the IE2 efficiency level and be equipped with a VSD.
3. From 1 January 2017, motors with a rated output of 0.75 – 375 kW must meet the IE3 efficiency level or meet the IE2 efficiency level and be equipped with a VSD.

An amendment of regulation No 4/2014 was then introduced in January 2014 [19], where the regulation on the subject matter and scope was updated and entered into force six months after its publication. The revised Ecodesign regulation No. 2019/1781 [9] was then published in October 2019 and the minimum efficiency requirements for motors are as follows.

1. From 1 July 2021:
    a. 2-, 4-, 6- and 8-pole, three-phase, not Ex eb increased safety motors with a rated output of 0.75 – 1000 kW shall correspond to at least IE3 efficiency level.
    b. 2-, 4-, 6- and 8-pole, three-phase, not Ex eb increased safety motors with a rated output of 0.12 – 0.75 kW shall correspond to at least IE2 efficiency level.
2. From 1 July 2023:
    a. 2-, 4-, 6- and 8-pole motors with a rated output of 0.12 kW - 1000 kW with extended safety class Ex eb, and single-phase motors with greater power than 0.12 kW shall correspond to at least IE2 efficiency level.
    b. 2-, 4- and 6-pole, three-phase, Ex eb increased safety motors with a rated output of 75 kW – 200 kW shall correspond to at least IE4 efficiency level.

Minimum efficiency requirements for VSD were also introduced in the revised Ecodesign regulation in 2019 [9].

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[1] Efficiency classes for single speed electric motors are rated according to IEC 60034-1 from the lowest (IE1) to the highest efficiency (IE4). [18]

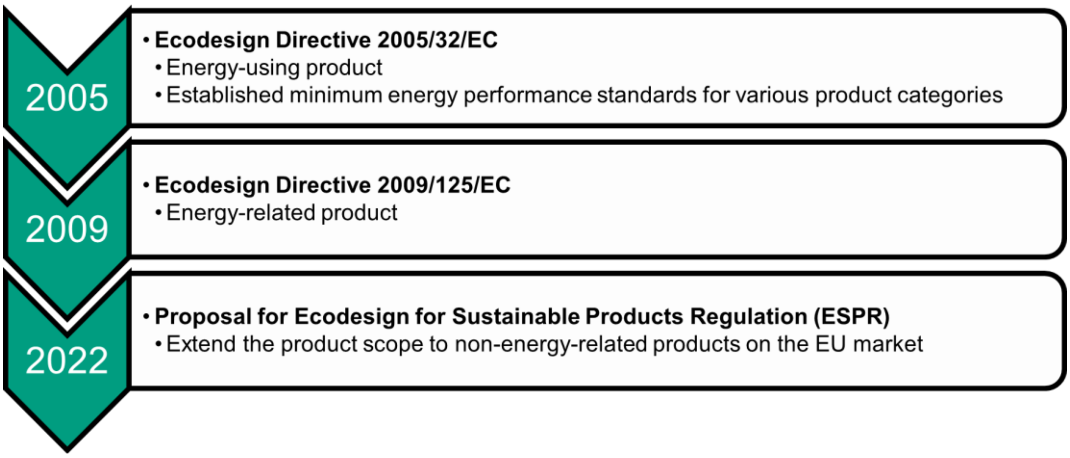
1. From 1 July 2021, the power losses of VSD rated for operating with motors with a rated output of 0.12 kW - 1000 kW shall not exceed the maximum power losses corresponding to the IE2 efficiency level.

A review study of Ecodesign product group regulations [15] found that there are no active circular economy requirements for electrical motors. Some general information requirements on disassembly, recycling and disposal were initially included, but they were taken out in 2019 after the review of the Ecodesign regulation for electric motors.

2.2. Ecodesign Directive

The Ecodesign Directive provides an EU-wide framework to improve the environmental performance of products on different life cycle stages and aspects. The Ecodesign Directive 2005/32/EC [20] was first established in 2005, setting Ecodesign requirements for energy-using products. It was then updated in 2009 (Ecodesign Directive 2009/125/EC [17], where energy-related products had to meet Ecodesign requirements before being placed in the market and put into service. In 2022, a proposal for Ecodesign for Sustainable Products Regulation (ESPR) [21] was made public to replace the current EU Ecodesign Directive, which will be broader in terms of product groups covered and types of requirements and measures. Under the Ecodesign and Energy Labelling Working Plan 2022-2024 [22], new regulations, preparatory studies and reviews will be carried out. An overview of the evolution of the Ecodesign Directive can be found in Figure 3.

To date, most of the implementing measures focus on energy efficiency during the use phase [23] by establishing the minimum energy performance standard (MEPS) for the product [24], but do not cover a lot of environmental performance issues. However, because of the increased consumption of primary resource-intensive consumer goods with short lifetimes such as smartphones and laptops, mainly focusing on energy efficiency during the use phase may not be sufficient [25]. For example, the preparatory study for smartphones revealed that the hotspot in the environmental impact assessment is not the use phase, but the production phase instead [26]. Due to the observed trend, recent preparatory studies have taken a holistic approach and attempted to deal with all relevant environmental impacts. As part of the CEAP, the European Commission (EC) implied that the scope will be extended in terms of products to also consider non-energy-related products and in terms of requirements, e.g. by incorporating circular economy aspects in the revision of existing and drafting of future Ecodesign requirements and by developing standards on material efficiency aspects [11]. All these trends and aspects lead to the necessity of updating the Ecodesign framework.



2005

- **Ecodesign Directive 2005/32/EC**
  - Energy-using product
  - Established minimum energy performance standards for various product categories

2009

- **Ecodesign Directive 2009/125/EC**
  - Energy-related product

2022

- **Proposal for Ecodesign for Sustainable Products Regulation (ESPR)**
  - Extend the product scope to non-energy-related products on the EU market

Figure 3: Overview of the evolution of Ecodesign Directive [17, 20, 21]

A preparatory study is carried out for products covered by the Ecodesign Directive. It is a technical study carried out on specific product groups to determine environmental impacts and recommend policy options for new Ecodesign regulations, with a standardised methodology, the MEErP [10].

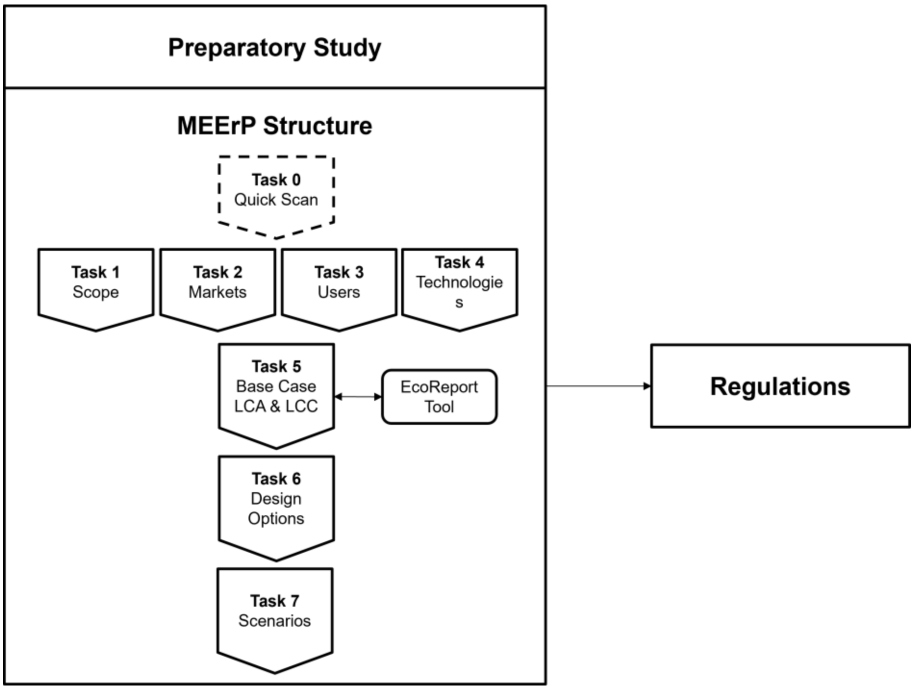


Figure 4: Overview of the link between preparatory studies, MEErP and regulations [27]

There is currently an ongoing review of the MEErP which aims to have a more systematic inclusion of the material efficiency and environmental aspects and to update the EcoReport tool [14]. According to the draft report by the Joint Research Centre (JRC) for the Review of the MEErP from 2021 [12], the impact categories selection in the revised EcoReport tool will be updated to the 16 impact categories used in the Environmental Footprint (EF) method, harmonising with the Product Environmental Footprint Category Rules (PEFCRs). Additional potential environmental impacts can be included and by default, the primary energy consumption is included since the methodology is used to analyse energy-related products in which energy consumption plays a vital role [12].

The current EOL modelling in the EcoReport tool predefines EOL mass fractions to calculate the credits. The model has different modelling assumptions for different materials, and this may lead to a high risk of inconsistencies in the final environmental impact results [27]. For example, metals have a fixed EOL mass fraction that could not be modified, and the recyclability benefit rate (RBR) calculation is only available for plastics.

As stated in the draft report by the JRC for the Review of the MEErP [12], the consistency and transparency of the EOL modelling are aimed to be improved through the implementation of a simplified version of the Circular Footprint Formula (CFF) (compared to the one used in the PEF) in the revised EcoReport tool. With the formula, recyclability and recycled content will be input parameters and can be modelled in the EOL scenario. In addition, the datasets in the revised EcoReport tool will be using EF 3.0 datasets, where the sources for each dataset should be more reliable and more representative of an average EU product along with the possibility of future regular updates [12].

Furthermore, material efficiency aspects are planned to be modelled consistently and systematically by introducing a discrete scoring system where the specific values are calculated using a Weibull lifetime distribution[2] model, and the approach for CRM will be updated as well in the revised EcoReport tool [12]. In short, the revised EcoReport tool will undergo an overhaul of the methodology and the outdated background data. A more detailed comparison of the current and revised EcoReport tool can be found in subchapter 2.3.

The current EcoReport tool is commonly used to justify that the use phase dominates the environmental impacts [29]. Studies will trust the results obtained from the tool and make assumptions when uncertainties occur to fit the purpose of their study [12]. It is uncertain if there is an assessment of the current EcoReport tool and its effectiveness to identify environmental impacts for products regulated under the Ecodesign framework. It is worthwhile noting that the review studies also play an important role in assessing the Ecodesign regulations as well. A study from 2017 [10] revealed that the preparatory study gets a higher budget compared to review studies and thus a thorough study can be carried out with the MEErP, but different approaches are often executed for review studies due to a lack of standardisation and a lower budget. This leads to environmental life cycle assessment (LCA) and life cycle cost (LCC) aspects not being fully investigated in some review studies, which are important tasks in the MEErP and will be crucial aspects for circular economy aspects under the Ecodesign framework. Shorter review deadlines are foreseeable in the future due to rapid changes in technologies, hence a standard procedure in reviews could be very beneficial with the addition of the revised MEErP for Ecodesign regulations.

2.3. Current and Revised EcoReport Tools

The EcoReport tool is an Excel-based, simplified life cycle-based tool to examine the environmental and energy aspects of the MEErP. For the current EcoReport tool, there are 3 released versions. In the Ecodesign Preparatory Study on Lot 11 Motors carried out by the Institute of Systems and Robotics - University of Coimbra (ISR-UC), the environmental impact assessment is based on the first version of the EcoReport tool, which was released in 2005. The second and third versions were released in 2011 and 2014 respectively, and there were added features such as the improved EOL modelling and CRM calculator [27].

The current EcoReport[3] tool has a simple design so that anyone can easily understand the overall approach and interpret the presented environmental impact results. The current EcoReport tool has mainly focused on the energy consumption and greenhouse gas (GHG) emissions aspects. The tool has a simple design and good accessibility as it is available to be downloaded for free on the EC's website, and these aspects of the tool are expected to be maintained in the revised version. The revised EcoReport tool also aims to place more focus on circular economy aspects such as recycled content and extended lifetime, which were not a focus in the current version.

The EcoReport tools have an input sheet to enter the relevant input parameters per life cycle phases to generate the environmental impact results based on the unit indicators. The results are summarized on a separate sheet, with the results being presented in different tables. The first table is the most important one that shows the environmental impacts per product over its lifetime. The impacts in the table are also divided into different life cycle stages. In the 2014 version of the current EcoReport tool, an additional sheet is also available to add extra materials and their relevant unit indicators, which can be chosen as input in the input sheet. Extra information such as the recycling benefit rate of plastics and CRM can also be calculated as well, but the output of these calculations is not reflected in the summarized results and are to be taken into account separately. The revised

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[2] Weibull distribution also known as Weibull lifetime distribution [28] is "a continuous probability distribution that can fit an extensive range of distribution shapes. It's frequently used in life data, reliability analysis, and warranty analysis to assess time to failure for systems and parts. The Weibull distribution has three parameters: the threshold or location parameter (γ) that defines the lowest possible value in a Weibull distribution, the shape parameter (β or k) that provides information about the failure rate, and the scale parameter (η or λ) that represents the variability present in the distribution."

[3] Unless specified, the term "current EcoReport tool" will be referring to the 2014 version.

EcoReport tool aims to incorporate all results from the additional information in the output results sheet.

2.3.1. Life Cycle Phases

Life cycle phases provide a framework for understanding and evaluating the environmental and economic impacts of a product or a service throughout its entire life span. Environmental impact hotspots and the dominant life cycle phases for the hotspots can then be pinpointed to identify areas to be prioritized for improvement.

The current EcoReport tool has four life cycle phases, which include the production (raw materials and manufacturing), distribution, use and EOL phases. The revised EcoReport tool consists of seven life cycle phases, which are raw materials, manufacturing, distribution, packaging, use, maintenance and repair, and EOL.

Table 1 compares the input data needed for the calculations in different life cycle phases in the current and revised EcoReport tools. The EOL phase will be excluded here as it will be covered in subchapter 2.3.3. Supplementary figures of the EcoReport tools can be found in Appendix 7.A.

Table 1: Inputs in the EcoReport tools for the calculation of the environmental impact

Life Cycle Phase	Current EcoReport Tool	Revised EcoReport Tool
Raw Materials	Material (share of secondary material predefined in some of the materials)	Primary and share of secondary material
Manufacturing	A list of fixed items with editable values [4]	Primary and share of secondary material, process, or energy
Distribution[5]	Product type (electronic or installed appliance) and final package volume	Transport means, transported product's weight, and transport distances
Packaging	Included in distribution	Primary and share of secondary material, process, or energy
Use	Product service life, energy consumption, and consumables (water and auxiliary materials)	Product service life, energy consumption, consumables (water, auxiliary, other materials) and direct emissions
Maintenance and Repair[6]	Included in the use phase: the distance that the spare parts travelled and a fixed 1% of product materials as spare parts	Spare parts as an editable percentage of product materials or material, process, or energy

2.3.2. Life Cycle Inventory Datasets

The life cycle inventory datasets in the EcoReport tool database are where the emission data for material, process or energy is extracted for the environmental impact calculation. As stated in the draft report by the JRC for the Review of the MEErP [12], the datasets have to comprise a typical bill of materials (BOM) of products under the Ecodesign Directive and can represent an average EU product. If the datasets include most of the important materials, the user will not need to make further

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[4] See Figure A 1 for a snippet of the current EcoReport tool manufacturing section.

[5] See Figure A 2 and Figure A 3 for a snippet of the EcoReport tools distribution section.

[6] See Figure A 4 and Figure A 5 for a snippet of the EcoReport tools maintenance and repair section.

assumptions about the data and the impact assessment results will have a lower risk of inconsistencies.

The datasets in the current EcoReport tool were extracted from various database sources [30] as public data on a homogenous average EU product was not available in 2005. At present, the datasets in the current EcoReport tool are mostly outdated. For example, the GHG emission intensity for the dataset electricity production is 0.38 kg CO_2 equivalent per kWh in the current EcoReport tool while the latest data from the European Environment Agency [31] states that one kWh of electricity generation emits 0.28 kg CO_2 equivalent of GHG. Datasets relating to electronics are also inadequate, whereby in the current EcoReport tool there are only 12 types of electronics to choose from in the list. Recycled material datasets for all materials types are also not present in the current EcoReport tool. Thus, the datasets have to be updated to be more extensive. Though, not many details on the exact sources of the datasets were available [12]. Hence, it is not favourable to update the datasets with the same approach.

In the revised EcoReport tool, the material datasets are updated based on the EF3.0 database. The database in the revised tool consists of primary and secondary materials, manufacturing processes and energy consumption. With the EF3.0 database, consistency and robustness across datasets are guaranteed along with possible regular updates in the future, and the database is also said to be a good representative of the average EU product [12]. There is also a dedicated new spreadsheet for the users to input additional datasets and extra information for products that are not from the EU. An overview of the material datasets in both EcoReport tools can be seen in Table 2.

Table 2: Current and revised EcoReport tool material datasets comparison

Current EcoReport Tool Material Category	Revised EcoReport Tool Material Category
1 – BlkPlastics	1 – Plastics, Recycled Plastics
2 – TecPlastics	
3 – Ferro	2 – Metals, Recycled Metals
4 – Non-Ferro	
5 – Coating	
6 – Electronics	3 – Electronics, Recycled Electronics
7 – Misc.	4 – Others, Recycled Others
8 – Extra	5 – Electricity
9 – Auxiliary	6 – Thermal energy
10 – Energy	7 – Boiler
11 – Refrigerant	9 – Transport

CRMs are raw materials that have high economic importance and are essential for a wide range of goods and applications but have a high risk of limited availability and supply disruption. For instance, lithium is a critical material that is essential in lithium-ion batteries for smartphones or energy storage systems, but the availability of economically viable lithium can be limited due to political factors or environmental concerns. In the context of the circular economy, CRMs are particularly important because they are often subject to significant extraction and processing impacts, both environmentally and socially. Additionally, their limited availability and potential supply chain disruptions make it crucial to adopt strategies that minimize their consumption and maximize their efficiency. Note that CRM is not relevant for this study as the BOM for the induction motor does not include any CRM.

CRMs are not included in the current EcoReport tool from 2005. The current EcoReport tool from 2011 includes the first list of CRMs[7]. The calculation for the impact of CRMs in the current EcoReport tool from 2011 and 2014 is based on a CRM index, where the quantity of material is multiplied by a

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[7] Refer to the left of Table A 1 for the list of CRMs in the current EcoReport tool.

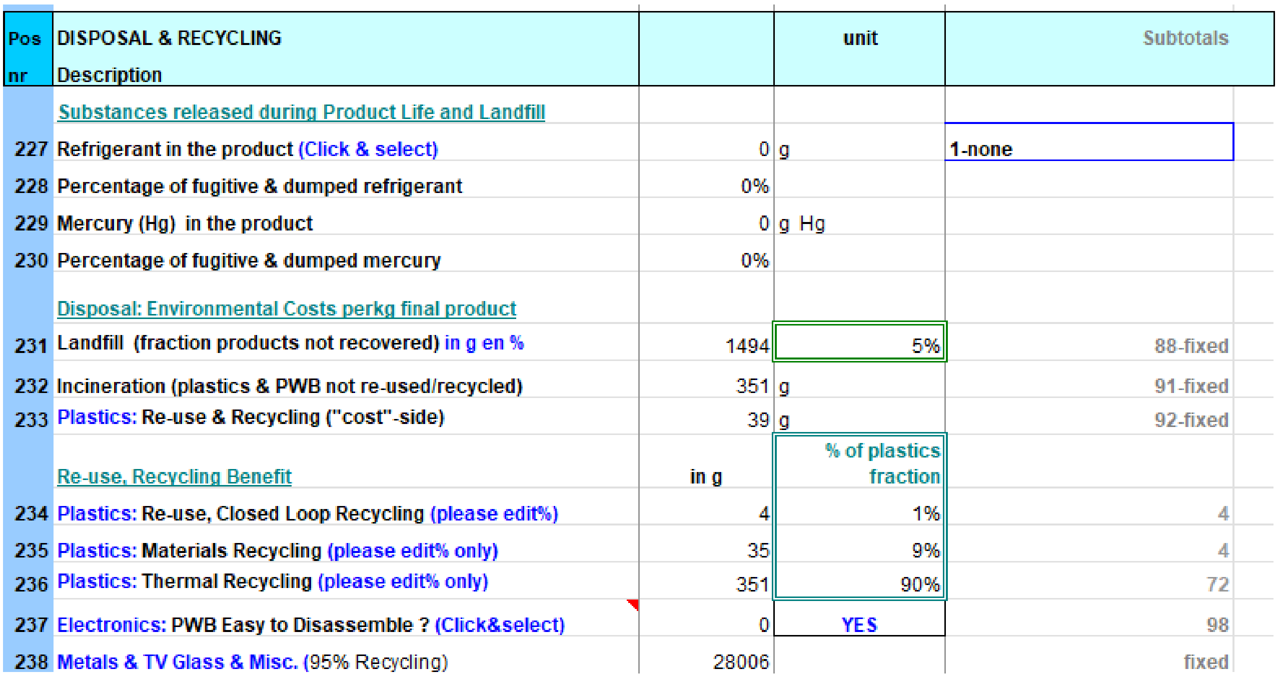
characterization factor[8] to calculate the Tungsten-equivalent [27]. In the draft report by the JRC for the Review of the MEErP [12], it is stated that the reasons for the concept of CRM equivalence are unclear and not well supported, and how the CRM index is associated with scarcity and environmental assessment is also ambiguous.

The revised EcoReport tool consists of a more elaborate CRM list[9] and assessment. In the revised EcoReport tool, a step-by-step approach will be taken for the assessment of the CRMs [12]. It will be built on the EC criticality assessment's latest numerical results and product groups with significant use of CRMs will be short-listed so that they can be prioritized[10]. Further details of the approach will not be discussed here.

2.3.3. End-of-Life

The EOL life cycle phase is significant in the context of the circular economy. Most products and materials that reached the end of their useful life will be disposed of if the reuse or recycling aspects are not economically beneficial. By implementing proper EOL management, opportunities to create a closed-loop system to promote resource efficiency or minimise waste can be realized, which offers both environmental and economic benefits. EOL modelling is included in the EcoReport tool to provide insights into the overall materials' EOL impacts and credits.

The EOL section of the current EcoReport tool from 2005 includes EOL aspects of the products as well as special cases such as refrigerants and mercury, but only the percentages are editable variables. Figure 5 shows a snippet of the EOL section from the 2005 current EcoReport tool.



Pos nr	DISPOSAL & RECYCLING Description		unit	Subtotals
	Substances released during Product Life and Landfill			
227	Refrigerant in the product (Click & select)	0	g	1-none
228	Percentage of fugitive & dumped refrigerant	0%		
229	Mercury (Hg) in the product	0	g Hg	
230	Percentage of fugitive & dumped mercury	0%		
	Disposal: Environmental Costs perkg final product			
231	Landfill (fraction products not recovered) in g en %	1494	5%	88-fixed
232	Incineration (plastics & PWB not re-used/recycled)	351	g	91-fixed
233	Plastics: Re-use & Recycling ("cost"-side)	39	g	92-fixed
	Re-use, Recycling Benefit	in g	% of plastics fraction	
234	Plastics: Re-use, Closed Loop Recycling (please edit%)	4	1%	4
235	Plastics: Materials Recycling (please edit% only)	35	9%	4
236	Plastics: Thermal Recycling (please edit% only)	351	90%	72
237	Electronics: PWB Easy to Disassemble ? (Click&select)	0	YES	98
238	Metals & TV Glass & Misc. (95% Recycling)	28006		fixed

Figure 5: EOL section of the current EcoReport tool from 2005

The EOL section of the current EcoReport then undergoes a complete review in 2011 to increase the transparency of the calculations. The recycling and recyclability aspects of other materials such as electronics and metals were added, and the material flows per EOL mass fraction are

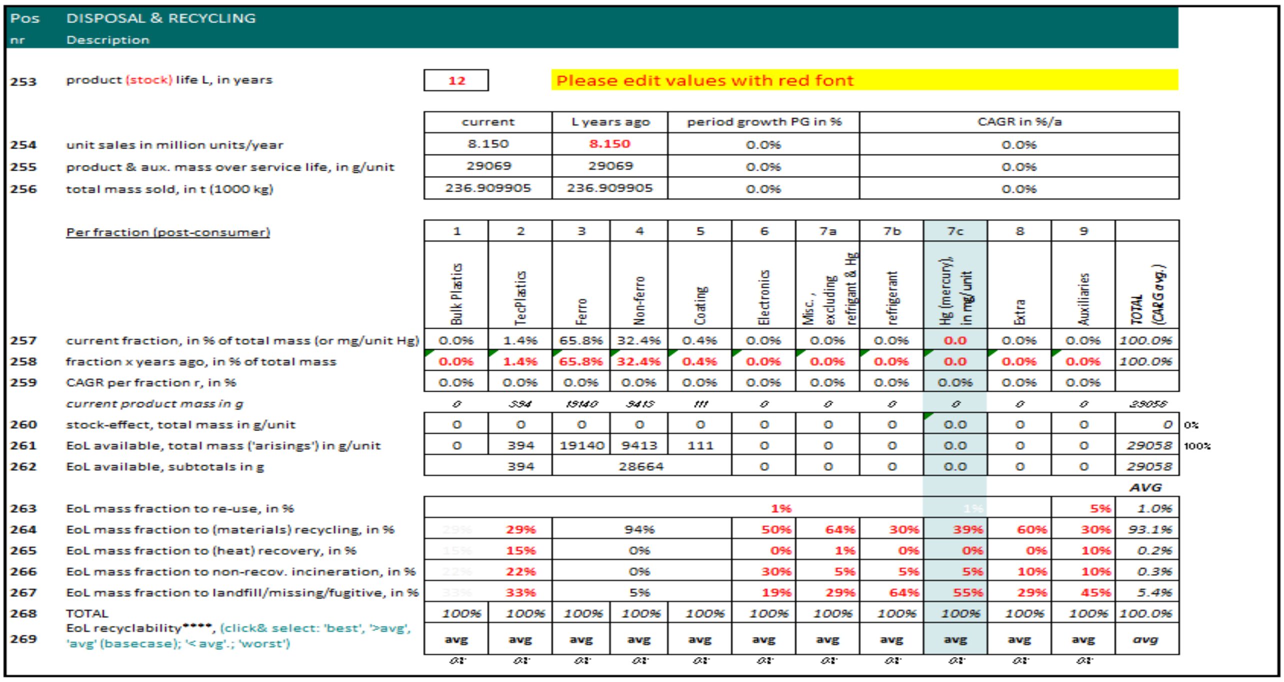
---

[8] See Figure A 6 for the characterization factor for the CRM indicator.

[9] Refer to the right of Table A 1 for the list of CRMs in the revised EcoReport tool.

[10] An example of short-listed CRMs and specific application derived from the criticality assessment can be seen in Figure A 7.

incorporated to calculate credits. Figure 6 shows a snippet of the EOL section from the 2011 and 2014 current EcoReport tools.

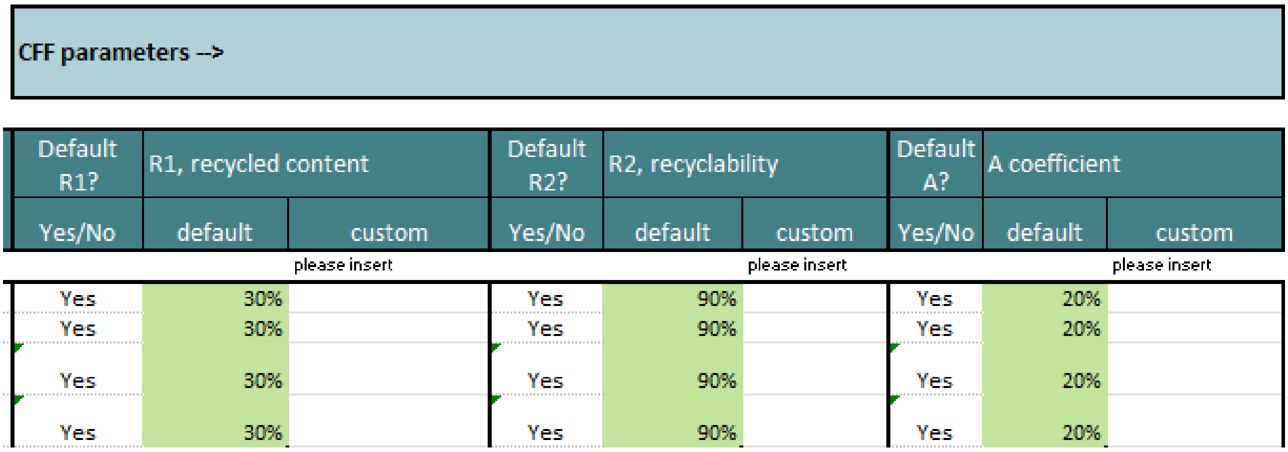


Pos nr	DISPOSAL & RECYCLING Description				
253	product (stock) life L, in years	12	Please edit values with red font		
		current	L years ago	period growth PG in %	CAGR in %/a
254	unit sales in million units/year	8.150	8.150	0.0%	0.0%
255	product & aux. mass over service life, in g/unit	29069	29069	0.0%	0.0%
256	total mass sold, in t (1000 kg)	236.909905	236.909905	0.0%	0.0%

Pos nr	Per fraction (post-consumer)	1 Bulk Plastics	2 TecPlastics	3 Ferro	4 Non-ferro	5 Coating	6 Electronics	7a Misc., excluding refrigant & Hg	7b refrigerant	7c Hg (mercury), in mg/unit	8 Extra	9 Auxiliaries	TOTAL (CARG avg.)	
257	current fraction, in % of total mass (or mg/unit Hg)	0.0%	1.4%	65.8%	32.4%	0.4%	0.0%	0.0%	0.0%	0.0	0.0%	0.0%	100.0%	
258	fraction x years ago, in % of total mass	0.0%	1.4%	65.8%	32.4%	0.4%	0.0%	0.0%	0.0%	0.0	0.0%	0.0%	100.0%	
259	CAGR per fraction r, in %	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%		
	current product mass in g	*0*	*394*	*19140*	*9413*	*111*	*0*	*0*	*0*	*0*	*0*	*0*	*29058*	
260	stock-effect, total mass in g/unit	0	0	0	0	0	0	0	0	0.0	0	0	*0*	0%
261	EoL available, total mass ('arisings') in g/unit	0	394	19140	9413	111	0	0	0	0.0	0	0	*29058*	100%
262	EoL available, subtotals in g	394		28664			0	0	0	0.0	0	0	*29058*	
													AVG	
263	EoL mass fraction to re-use, in %						1%			1%		5%	*1.0%*	
264	EoL mass fraction to (materials) recycling, in %	29%	29%	94%			50%	64%	30%	39%	60%	30%	*93.1%*	
265	EoL mass fraction to (heat) recovery, in %	15%	15%	0%			0%	1%	0%	0%	0%	10%	*0.2%*	
266	EoL mass fraction to non-recov. incineration, in %	22%	22%	0%			30%	5%	5%	5%	10%	10%	*0.3%*	
267	EoL mass fraction to landfill/missing/fugitive, in %	33%	33%	5%			19%	29%	64%	55%	29%	45%	*5.4%*	
268	TOTAL	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100.0%*	
269	EoL recyclability****, (click& select: 'best', '>avg', 'avg' (basecase); '< avg'.; 'worst')	avg	avg	avg	avg	avg	avg	avg	avg	avg	avg	avg	*avg*	

Figure 6: EOL section of the current EcoReport tool from 2011 and 2014

A simplified version of the Circular Footprint Formula (CFF) is then proposed to be implemented in the revised EcoReport tool for the EOL modelling. Parameters such as recycled content and recyclability will be modelled using the CFF. The simplified CFF excludes the energy and disposal calculation, which are defined in the EF method as their contribution to the life cycle impact of energy-related products is considered to be minor.



CFF parameters -->

Default R1?	R1, recycled content		Default R2?	R2, recyclability		Default A?	A coefficient	
Yes/No	default	custom	Yes/No	default	custom	Yes/No	default	custom
		please insert			please insert			please insert
Yes	30%		Yes	90%		Yes	20%	
Yes	30%		Yes	90%		Yes	20%	
Yes	30%		Yes	90%		Yes	20%	
Yes	30%		Yes	90%		Yes	20%	

Figure 7: EOL section of revised EcoReport tool

The following is the proposed simplified CFF which is extracted directly from the draft report by the JRC for the Review of the MEErP [12]:

$$(1 - R_1)E_V + R_1 \times \left(AE_{recycled} + (1 - A)E_V\right) + (1 - A)R_2 \times \left(E_{recycledEOL} - E_V^*\right) \qquad (1)$$

where the terms in the formula are defined as following from the same source:

R_1 (recycled content): The proportion of material in the input to the production that has been recycled from a previous system.
R_2 (recycling output rate): The proportion of the material in the product that will be recycled (or reused) in a subsequent system. It takes into account the inefficiencies in the collection and recycling (or reuse) processes and will be measured at the output of the recycling plant.
A (allocation factor): The allocation factor of burdens and credits between supplier and user of recycled materials.
$E_V = E_V^*$: The specific emissions and resources consumed (per functional unit) arising from the acquisition and pre-processing of virgin material.
$E_{recycled} = E_{recycledEOL}$: The specific emissions and resources consumed (per functional unit) arising from the recycling process of the recycled (reused) material, including collection, sorting, and transportation process.

The default values for the terms are from the EF method and will be provided in the revised EcoReport tool.

2.3.4. Material Efficiency

Material efficiency is the concept of optimizing the use of materials while maintaining the function of the product or service. The goal is not only to reduce the amount of materials used but also to realize environmental gains [32]. It is important that the EcoReport tool can identify environmental hotspots linked to material efficiency aspects with the upcoming ESPR.

Material efficiency aspects are partially modelled in the current EcoReport tool. In the 2005 current EcoReport tool, it is only possible to input the percentage of plastic fractions that are recycled or reused for the EOL. As mentioned in 2.3.3, the EOL modelling was then updated in 2011 and 2014 to introduce the recycling and recyclability aspects to all materials. It was also possible to calculate the recycling benefit rate in the current EcoReport tool from 2011 and 2014. However, it is only possible for plastics.

According to the draft report by the JRC for the Review of the MEErP [12], the durability of the product is modelled as one of the material efficiency aspects in the revised EcoReport tool. Durability represents the total expected lifetime estimation and depends on three variables, reliability, repairability and upgradability. The values for the variables are calculated with a Weibull lifetime distribution model and are put in a discrete-step scoring system. The reliability is based on the initial lifetime expectation and is the first limiting event for durability. Lifetime extensions are estimated through repairability and upgradability scoring levels. Material efficiency aspects such as recycled content and recycling output rate are parameters in the simplified CFF, which are used to model the EOL phase of materials [12].

2.3.5. Impact Categories

One important aspect of the impact categories in the EcoReport tool is that the impact categories should be not too comprehensive and be able to represent important prospects. The environmental impact results should also be easily interpretable and are transferable or comparable to other studies.

The impact categories in the current EcoReport tool are based on parameters that are deemed important in the context of energy-using products back in 2005 [30] and the impact categories in the revised EcoReport tool are based on the PEF. While several impact categories overlap, such as ozone depletion and particulate matter, climate change and primary energy are the only impact categories expressed in the same unit, but even so the methods of calculation are not identical. A comparison of the impact categories in the current and revised EcoReport tools can be found in Table 3.

Table 3: Current and revised EcoReport tool impact categories comparison, adopted from [27, 33, 34]

Impact Category	**Current EcoReport Tool**		**Revised EcoReport Tool**	
	Indicator	**Unit**	**Indicator**	**Unit**
Climate change	GHGs, global warming potential (GWP 100)	kg CO_2 equivalent	Bern model, GWP 100	kg CO_2 equivalent
Ozone depletion	Ozone depletion, emissions (Removed in 2011 due to negligible emissions)	g R-11 equivalent	Ozone depletion potential	kg CFC-11 equivalent
Human toxicity, cancer			Comparative Toxic Unit for humans	CTUh
Human toxicity, non-cancer			Comparative Toxic Unit for humans	CTUh
Particulate matter	PM, dust	g	Human Health effect	Disease incidence
Ionising radiation, human health			Potential for human exposure relative to U235	kBq U235 equivalent
Photochemical ozone formation, human health	Volatile Organic Compounds (VOC)	g	Tropospheric ozone concentration increase	kg NMVOC equivalent
Acidification	Acidification, emissions	g SO_2 equivalent	Accumulated Exceedance	mol H+ equivalent
Eutrophication, terrestrial			Accumulated Exceedance	mol N equivalent
Eutrophication, fresh water	Eutrophication, water	g PO_4	Nutrient emissions fractions	kg P equivalent
Eutrophication, marine			Nutrient emissions fractions	kg N equivalent
Ecotoxicity, freshwater			Comparative Toxic Unit for Ecosystems	CTUe
Land use			Soil quality index	Dimensionless (pt)
Water use	Water, process and cooling	litres	Swiss Ecoscarcity	m3 water use related to local scarcity of water

Resource use, minerals and metals	Listed as bulk plastics, Ferro, electronics etc.	g	Abiotic resource depletion potential, ultimate reserve	kg antimony (Sb) equivalent
Resource use, fossils	Total energy (GER), of which, electricity	MJ	Abiotic resource depletion potential, fossil	MJ
Waste	Waste, non-hazardous/landfill and hazardous/incinerated	g		
Emissions to air	• Persistent organic pollutants (POP) • Heavy metals • Polycyclic aromatic hydrocarbons (PAH)s	• ng i-Teq • mg Ni equivalent • mg Ni equivalent		
Emissions to water	• Heavy metals • Persistent organic pollutants (POP) ((Removed in 2011 due to negligible emissions)	• mg Hg/20 • mg		

Note: Grey-shaded boxes indicate that the impact category is not included in the EcoReport tool.

2.4. Life Cycle Assessment

Life cycle assessment is a methodology used to evaluate the environmental impacts of a product at all life cycle stages from cradle-to-grave [35]. ISO 14040/44 [36, 37] is the standard methodology for practising LCA where basic requirements for conducting an LCA are provided. An LCA study consists of four phases: goal and scope definition, inventory analysis, impact assessment and interpretation. The end application depends on the audience and purpose of the assessment. Defining the goal and scope are important steps as they determine the boundary of data collection for the system model and can highly influence the end LCA results. Inventory analysis documents the inputs and outputs flow of each unit process within the product system. It is important to consider the selection, classification and characterization of the impact category that will be the most relevant to the study. During interpretation, sensitive analysis and quality checks may be carried out to further strengthen conclusions and check the robustness of the results. When in any doubt, the LCA practitioner should always refer back to the goal and scope defined in the beginning. The International Life Cycle Data System (ILCD) [38] also provides additional guidelines for LCA to ensure the consistency and quality of life cycle studies.

2.5. Circular Economy

The concept of circular economy as defined by the EU [39] has the aim to minimize the generation of waste while maximizing the value of products, materials, and resources by reintroducing them into the product cycle after the end of their use. The concept is built on the 3R principles which are reduce, reuse, and recycle [40]. Reduce aims to minimize the materials and energy used as well as the waste generated, by increasing efficiency in production and consumption, for example by using energy-efficient appliances. Reuse is to utilise products and components that are not waste, again for the same function that they were originally designed for or repurposed for a different function [41, 42]. Reuse has the potential to improve overall resource efficiency as reusing products and components can require fewer resources and energy compared to producing new products and components, and it can also benefit from the multiple-use cycle [40]. Recycle refers to any recovery operation where waste is processed into products, materials or substances, whether for the original or other purposes [41]. Recycling should be the last resort as it is the least sustainable solution of the 3R principles, but it is often equated with circular economy as it is common for policies to aim for increasing recycling rates [43].

There are different circular economy frameworks other than the 3R principle. For example, the EU Waste Framework Directive adopts the 4R framework which includes the “recover” principle, which refers to waste that is put to a useful purpose by substituting materials or waste being prepared to fulfil a particular function [41]. There are also 6R and 9R frameworks, which aim to capture more nuances, but this study will be using the 3R framework for simplicity’s sake as the definition can get ambiguous and overlapping with various R’s [43]. It is important to note that the term circular economy can be vague as it can be conceptualized in different definitions and dimensions across studies [43].

The linear economy is a system where the products go from cradle to grave. With this system, it is rather counter-intuitive to be mindful of resource efficiency which can lead to a disproportionate level of waste output [44, 45]. The products in the circular economy model go from cradle to cradle instead, where products or resources are placed back into the cycle to eliminate waste and reduce the use of new resources. Currently, the concept of circular economy is widely promoted and gaining traction as resource scarcity issues are escalating.

3. Phase 1: EcoReport Tool

3.1. Method

Firstly, the studied case is determined. Then, the following subchapters will provide the data source for the necessary input values of an individual base case electric motor required to calculate the environmental impacts via the EcoReport tools. Lastly, the environmental impact results are examined, and circular economy measures are identified from the hotspots. It is important to note that the datasets in the revised EcoReport tool consist of dummy values as it is not finalized yet. The outcome of the impact assessment results will not be accurate and hence the focus here will be to investigate the approach and not the accuracy of the results.

3.1.1. Studied Case

The product for the case study is a 3-phase induction motor as it has the highest market share in terms of units sold in the EU market. The standard base cases are defined as a typical motor on the market for three different reference output powers 1.1 kW, 11 kW and 110 kW. The functional unit is defined as the provision of mechanical power by electrical motors with 1.1 kW, 11 kW and 110 kW nominal power at 2000 hours a year in their respective average service life.

The ISR-UC provided the EcoReport tool files from the Ecodesign Preparatory Study on Motors in 2008 and the most recent BOM for electric motors, which uses the current EcoReport tool from 2005. In the following subsections, the results of the current EcoReport tool refer to the one provided by ISR-UC. According to ISR-UC (personal communication, November 2022), they have looked into different load factors for the motors. For this analysis, the motor load factor for which energy consumption is responsible for the lowest possible impact is considered. Since the motor's energy consumption in the use phase contributes to more than 80% of the environmental impact [46], the specification is made to ensure that other hotspots are still identifiable. The data provided by ISR-UC considered an average load factor of 60%.

3.1.2. Raw Materials and Manufacturing Inputs

The BOM that consists of the material composition of induction motors is provided by ISR-UC and can be seen in Table 4. The BOM is used as inputs for the raw materials life cycle phase (and the packaging phase in the revised EcoReport tool).

Table 4: Bill-of-Materials for IE3 and IE4 induction motors (personal communication with ISR-UC, November 2022)

Material	**Motor Rated Power**					
	1.1 kW		**11 kW**		**110 kW**	
Motor Efficiency Level	**IE3**	**IE4**	**IE3**	**IE4**	**IE3**	**IE4**
Electric steel [kg/k]	11.00	15.36	6.36	8.46	4.18	4.90
Other steel [kg/kW]	1.68	1.77	1.05	1.11	0.73	0.76
Cast iron [kg/kW]	4.55	4.55	3.73	3.73	3.00	3.00
Aluminium [kg/kW]	0.75	0.89	0.40	0.45	0.22	0.25
Copper (winding) [kg/kW]	2.55	3.55	1.25	1.75	0.65	0.73
Copper (leads) [kg/kW]	0.03	0.03	0.02	0.02	0.01	0.01
Insulation material [kg/kW]	0.05	0.05	0.02	0.02	0.01	0.01
Impregnation resin [kg/kW]	0.30	0.30	0.10	0.10	0.05	0.05
Paint [kg/kW]	0.10	0.10	0.05	0.05	0.01	0.01
Packaging [kg/kW]	1.00	1.00	0.90	0.90	0.50	0.50

According to the Ecodesign Preparatory Study on Lot 11 Motors [13], the material fractions are only an average value. Depending on the different designs, the material value can deviate by around 40%. As the current EcoReport tool assumes a fixed 1% of the total material weight as spare parts and it is considered inadequate, the ISR-UC introduced the equivalent replacement windings and bearings directly in the BOM as well, but the exact materials and amount were not communicated. The inputs for manufacturing are obtained directly from the EcoReport tool files provided by ISR-UC and adjusted to be used in the revised EcoReport tool.

3.1.3. Distribution Inputs

In the MEErP Methodology Report 2011 [47], it is stated that the current EcoReport tool model automatically assumes a 200 km distance for the first trip of goods from the retailer (or manufacturer) to the shop, and from the shop, products are assumed to travel another 20 km to their final destination. The volume of the package is the input required for the calculation of the environmental impact in the distribution phase in the current EcoReport tool and is provided by ISR-UC. In the Ecodesign Preparatory Study on Lot 11 Motors [13], the distance covered over the motor life for maintenance and repair is assumed to be around 250 km. These inputs are referenced and used in the revised EcoReport tool.

3.1.4. Use Phase Inputs

According to the Ecodesign Preparatory Study on Lot 11 Motors [13], electric motors are considered energy converters, with the remaining consumed energy transmitted as mechanical energy to the end-use device. Hence in the use phase, only the energy losses are considered for the environmental analysis. The inputs for the use phase are obtained from the Ecodesign Preparatory Study on Lot 11 Motors [13] and are adjusted accordingly. 4-pole motors are considered for the inputs as they dominate the low voltage 3-phase induction motors market. An overview of the use phase inputs can be seen in Table 5.

Table 5: Use phase inputs [13]

Variable	**Motor Rated Power**		
	1.1 kW	**11 kW**	**110 kW**
Average expected lifetime [years]	12	15	20
Efficiency (IE3) [%] [9]	84.1	91.4	95.4
Efficiency (IE4) [%] [9]	87.2	93.3	96.3
Operating hours p.a.	2000	2000	2000
Distance covered over motors' lifetime [km]	450	450	450

3.1.5. Maintenance and Repair, and EOL Inputs

For maintenance and repair, the default value of 1% of the total input material is used in both EcoReport tools to maintain consistency. For the EOL, the default values for the CFF parameters, which are not aligned with Annex C[11] yet at the time of writing, are used as well, except for copper as the material that is aimed to be investigated.

According to the European Copper Institute (personal communication, February 2022), the recycling rate of copper from AC motors is around 42%. The estimated percentage of recycled copper used in producing AC motors depends on how the quantity is measured. Recycled content should be measured before the semi-finished products are entered into use and should consider all secondary

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[11] Default values of recycled content R_1 and recycling output rate R_2 are provided by the EF method in the "Annex C" in the revised EcoReport tool which can be found here: http://eplca.jrc.ec.europa.eu/LCDN/developerEF.xhtml [12]

sources. The estimated recycled content is around 46%. However, the European Copper Institute also made a disclaimer that the estimation is purely theoretical because it measures the average recycled content of the semi-finished products output pool in the EU. These statements are taken into account for the input parameters for copper.

It is also mentioned by the European Copper Institute that all recycled copper can reach the same quality and purity as virgin material flows after processing. However, it is important to note that for a shredder-based recycling process, such material recovery is not likely [48] and the recycling of small electric machines is often shredder-based [49].

3.2. Results

The first research sub-question is addressed in this subchapter. The environmental impact results from the current EcoReport tool per life cycle phase for an IE3 1.1 kW induction motor are displayed in Figure 8. Based on the results, it can be seen that most of the environmental impacts are dominant in the use phase. In total energy, electricity, water process and cooling, GHG, VOC, and PM, the use phase makes up more than three-quarters of the impacts. In hazardous waste, acidification and PAHs, the use phase makes up around two-thirds of the impacts. In non-hazardous waste, POP, heavy metals emission from air and water, and eutrophication, the environmental impacts are dominant in the production phase.

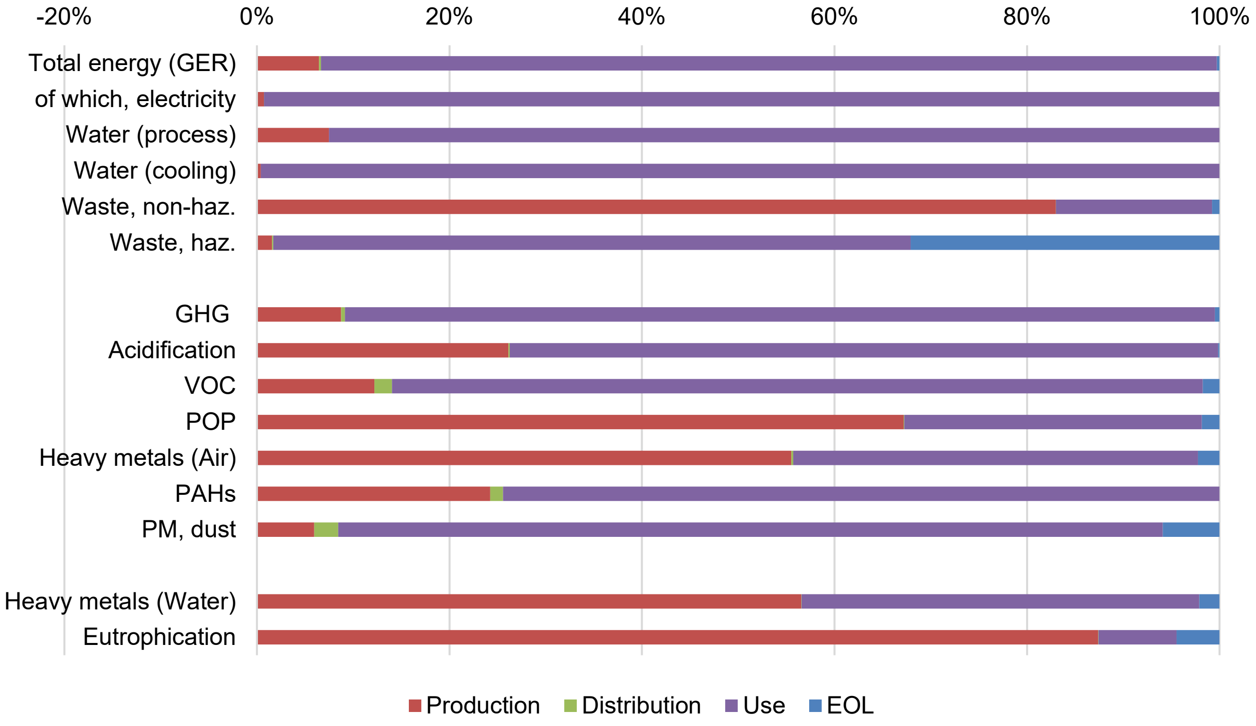

Figure 8: Environmental impacts results from current EcoReport tool, share per life cycle phase for IE3 1.1 kW induction motor

The data is then normalised against the share of EU totals, which are information provided in the current EcoReport tool from 2014, to examine the relative share of each impact category in the EU

[29]. For this product, electricity has the highest share of 0.81%[12] and will be the basis of the normalisation. The results are shown in Figure 9 and overall, the use phase is still the dominant life cycle phase for most of the environmental impacts. The top three hotspots identified are electricity, PM and acidification.

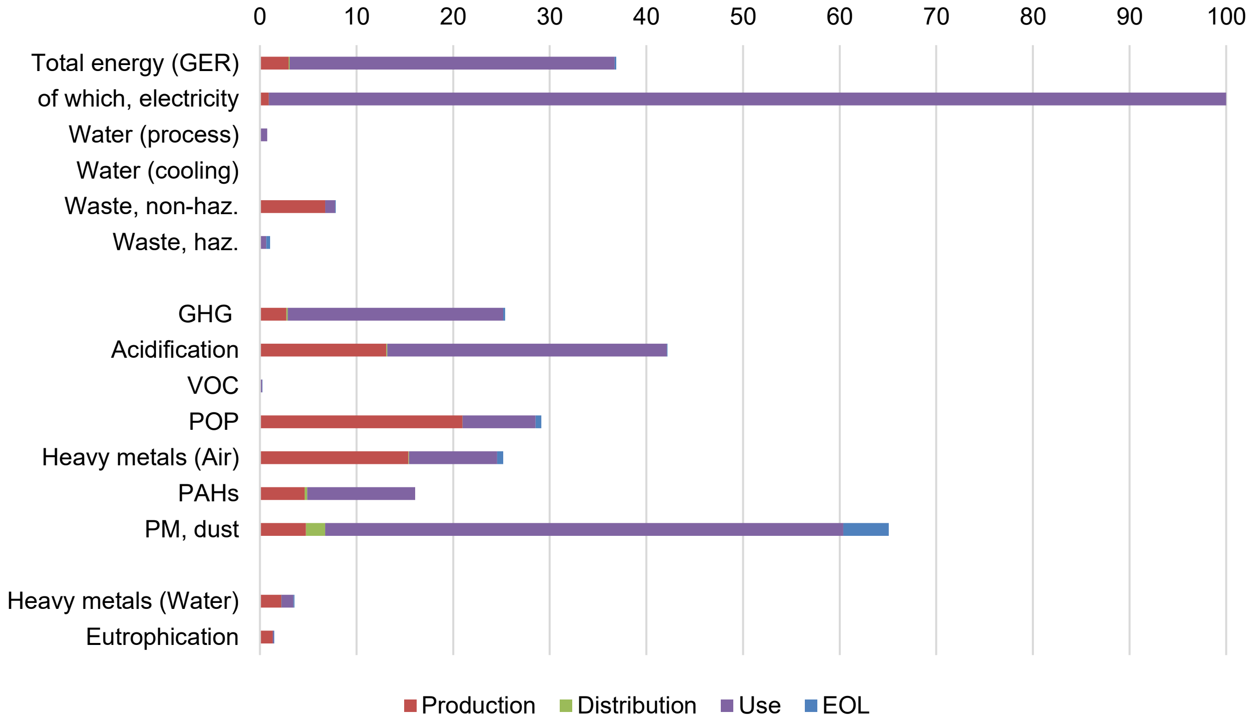

Figure 9: Environmental impacts results from current EcoReport tool, normalized share per life cycle phase (electricity = index 100 = 0.81% EU total share) for IE3 1.1 kW induction motor

The environmental impact results from the revised EcoReport tool per life cycle phase for an IE3 1.1 kW induction motor are displayed in Figure 10. In climate change, PM, ionising radiation, photochemical ozone formation, eutrophication terrestrial and marine, ecotoxicity, land use, water use, and fossil use, the use phase makes up more than two-thirds of the impacts. Ozone depletion and acidification are dominant in both the raw materials phase and the use phase. The raw materials phase makes up around three-quarters of human toxicities and freshwater eutrophication impact, and the impact of minerals and metals use is dominant in the manufacturing phase.

Normalisation against the share of EU totals is not carried out as the information is not available in the revised EcoReport tool which is not finalised yet. Instead, PEF normalization factors and weighting factors [50, 51] are used to identify the most relevant impact categories following the instructions from the PEF guide [33]. The results are shown in Figure 11 and based on the results, the top three hotspots identified with a cumulative 80% threshold across all life cycle stages are land use, fossils use, and freshwater ecotoxicity. The use phase is the dominant life cycle phase for the mentioned environmental hotspots.

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[12] Refer to Table A 2 for the share of EU totals.

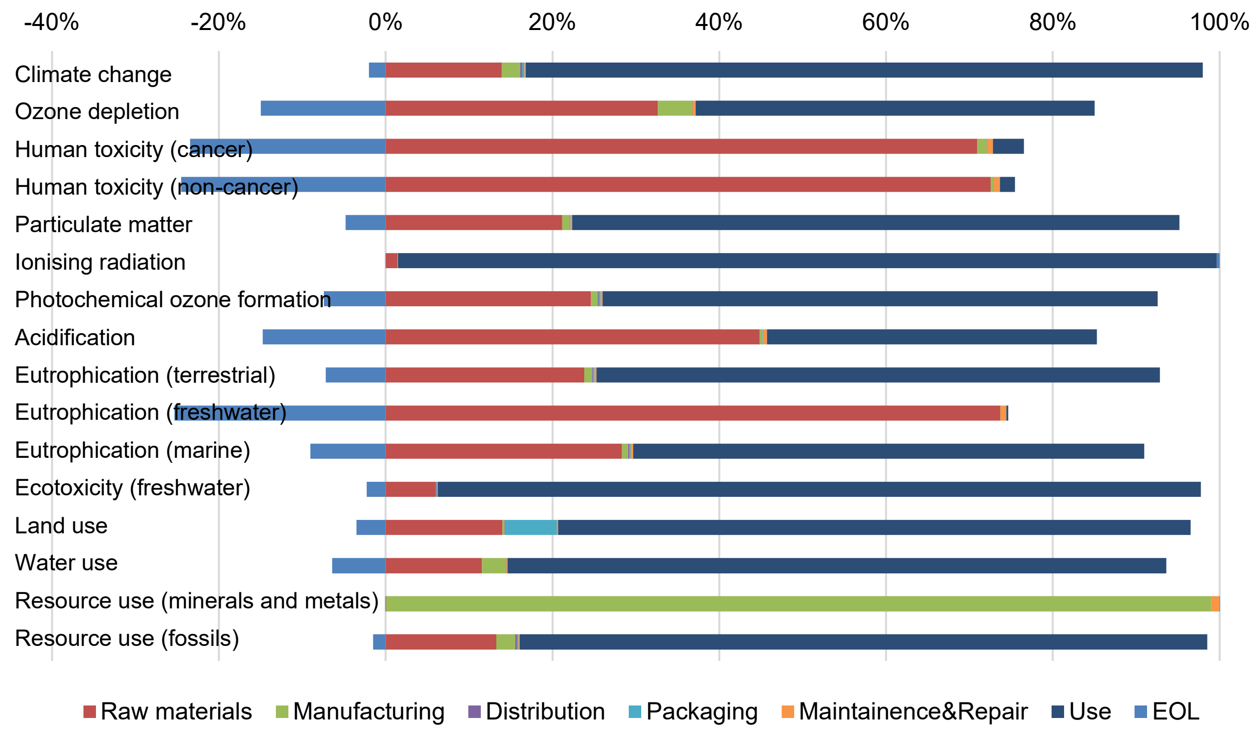


Figure 10: Environmental impacts results from revised EcoReport tool, share per life cycle phase for IE3 1.1 kW induction motor

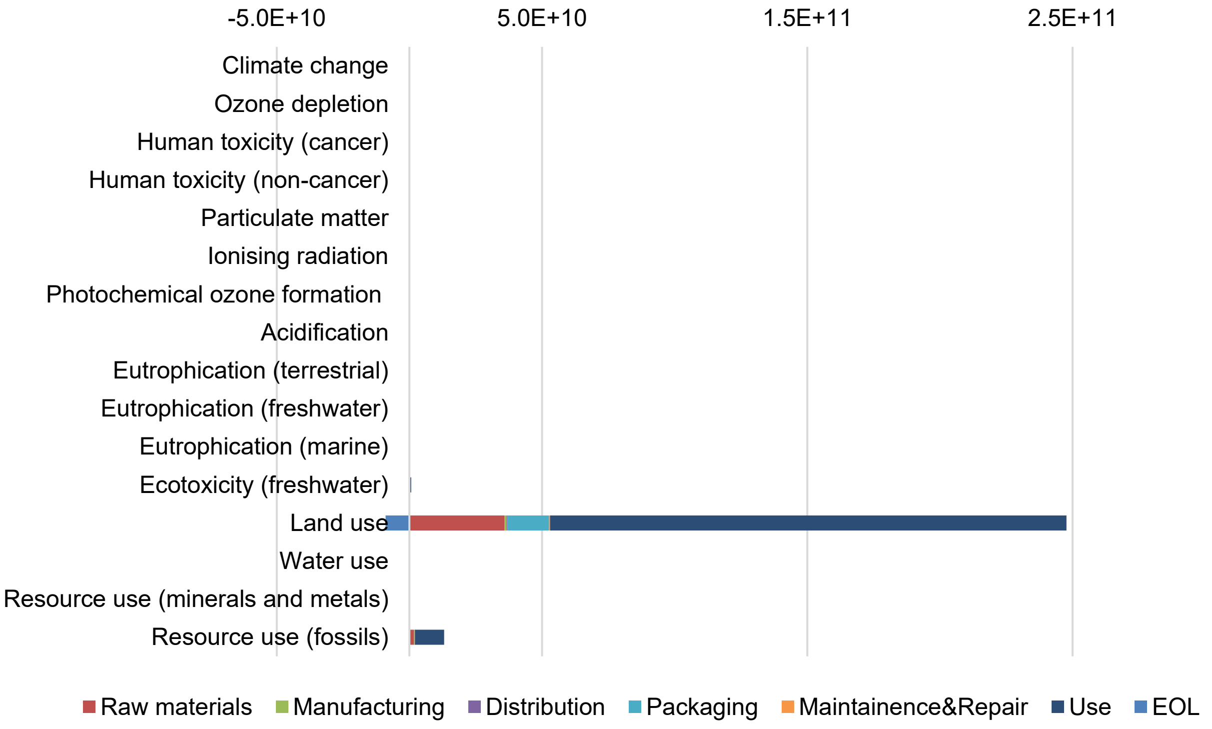


Figure 11: Environmental impacts results from revised EcoReport tool, normalized and weighted share per life cycle phase for IE3 1.1 kW induction motor

To have a better perspective on the environmental impacts of the other stages, the results from the revised EcoReport tool are also displayed in Figure 12 without the domineering use phase. Without the use phase, the raw materials phase is the dominant phase. Figure 12 also shows that land use is the most relevant impact in all phases.

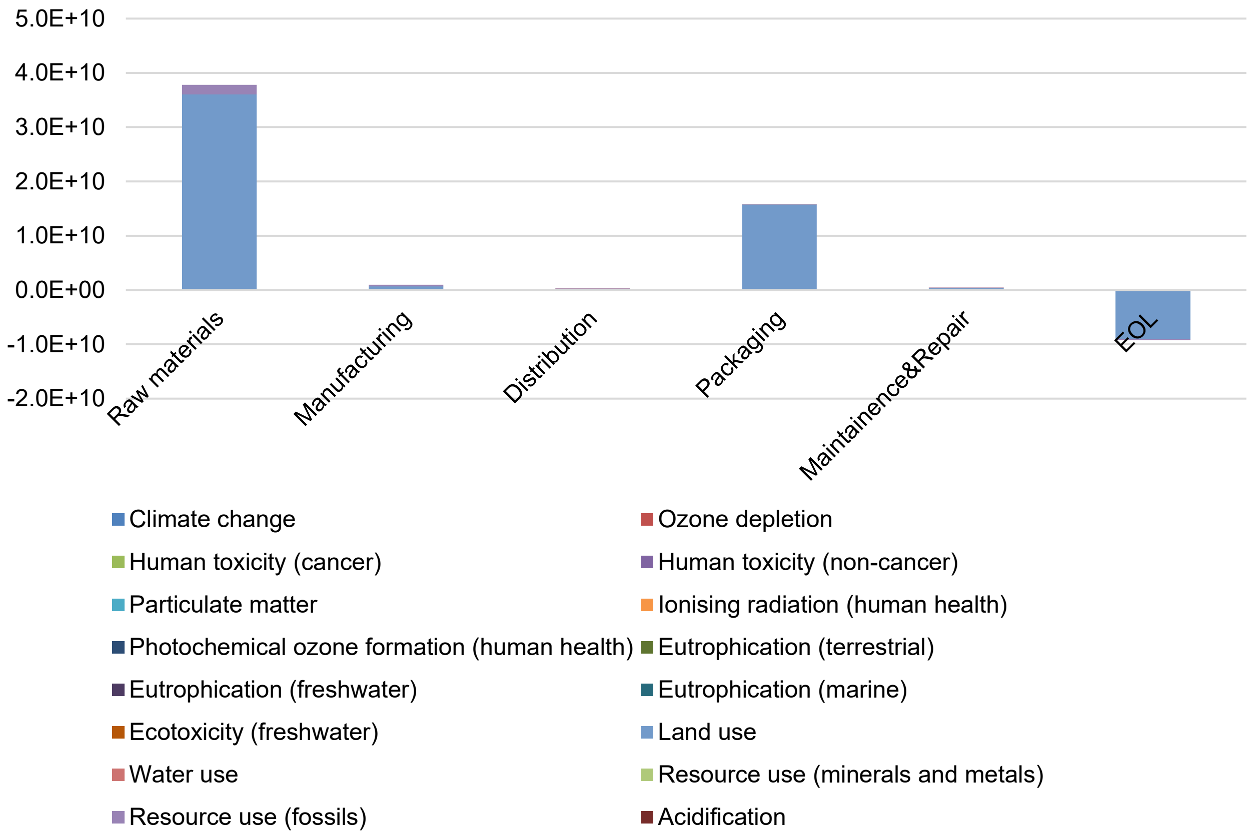


Figure 12: Environmental impacts results from revised EcoReport tool, normalized, weighted, and aggregated share per life cycle phase for IE3 1.1 kW induction motor without the use phase

The impacts in the use phase dominate the life-cycle impact of the standard case motors in both EcoReport tools (detailed results in Table A 3 and Table A 4). The main contributors for the top three environmental impact hotspots from both EcoReport tools are determined and possible circular economy measures are identified based on the results. A summary can be seen in Table 6.

The environmental impact results for IE3 11 kW and IE3 110 kW from both EcoReport tools can be found in Annex I, and the conclusions drawn from these results are similar to the findings for IE3 1.1 kW motor.

Table 6: Possible circular economy measures for the environmental impact hotspots

Environmental Impact Hotspot	**Main Contributor**	**Possible Circular Economy Measure**
Current EcoReport tool		
Electricity	Electricity	Motors' energy efficiency improvement, renewable energy for electricity production
PM	Landfill	Waste minimization strategies, improve waste management systems
Acidification	Copper, electricity	Secondary source for copper, increase copper's recyclability, renewable energy for electricity production
Revised EcoReport tool		
Land use	Copper, electricity	Secondary source for copper, increase copper's recyclability, renewable energy for electricity production
Resource use, fossils	Electricity	Motors' energy efficiency improvement, renewable energy for electricity production
Ecotoxicity, freshwater	Copper, electricity	Secondary source for copper, increase copper's recyclability, renewable energy for electricity production

3.2.1. Sensitivity Analysis

Since the use phase in which electricity is the main contributor to the environmental impacts, sensitivity analyses are carried out on the source of electricity production. Different datasets for electricity are explored, however, this option is only available in the revised EcoReport tool. Table 7 compares the environmental impact of electricity from wind and photovoltaic (PV) to electricity grid mix for an IE3 1.1 kW motor with a lifetime of 12 years and operation of 2000 hours per year. The results highlight that electricity from wind and PV can significantly reduce most environmental impacts, emphasizing the substantial influence of the energy source on the environment. Though, achieving 100% electricity production from renewable sources is currently not feasible.

Table 7: Sensitivity analysis on electricity production for IE3 1.1 kW induction motors

Impact Category	**Electricity from Wind (EU Mix)**	**Electricity from PV (FR)**
Climate change	-84.3%	-76.2%
Ozone depletion	-71.0%	-67.4%
Human toxicity (cancer)	18.6%	-6.2%
Human toxicity (non-cancer)	-3.8%	-1.3%
Particulate matter	-80.6%	-25.6%
Ionising radiation (human health)	-98.2%	-94.3%
Photochemical ozone formation (human health)	-78.1%	-64.2%
Acidification	-58.0%	-50.2%
Eutrophication (terrestrial)	-78.6%	-69.6%
Eutrophication (freshwater)	-0.5%	-0.4%
Eutrophication (marine)	-75.0%	-66.6%
Ecotoxicity (freshwater)	-94.9%	-80.2%
Land use	-81.2%	-72.6%
Water use	-91.3%	-79.1%
Resource use (minerals and metals)	0.0%	0.0%
Resource use (fossils)	-85.3%	-77.8%

3.3. Summary

This section introduced the studied case and the type of inputs required for the environmental impact assessment of the induction motors. The environmental impact of an IE3 1.1 kW induction motor is analysed using both EcoReport tools and presented above.

The results show that for both EcoReport tools, the use phase dominates the majority of environmental impact. The environmental impact results are normalized (and weighted for the revised EcoReport tool results) to identify the hotspots. The main contributors to the environmental hotspots are identified as well and possible circular economy measures to reduce the environmental impacts based on the hotspots and contributions are determined. Sensitivity analysis on the source for electricity production is also carried out as electricity in the use phase is the major contributor to the environmental hotspots.

4. Phase 2: Circular Economy Measures

Circular economy strategies such as the 3R can be applied to electric motors. For reduce, measures such as design for durability by e.g. using high-quality materials can be applied, so that motors can last longer and need to be replaced less frequently.

Measures such as remanufacturing and refurbishing of the electric motors can be categorized under the reuse strategy. According to the Technical Report CLC/TR 45550:2020, remanufacturing is defined as "an industrial process which produces a product from used products or used parts where at least one change is made which influences the safety, original performance, purpose or type of the product", while refurbishing is explained as a "similar concept to remanufacturing, but it does not involve changes influencing safety, original performance, purpose or type of the product". Refurbishing can involve replacing outdated components with more efficient ones or adding new features that improve the motor's performance. Simply repurposing an old functional motor in another application is also a possible circular economy measure. However, it is to note that there may be material rebound effects even though this technically reduces waste by not scrapping or recycling the still functional motor. The reuse strategy can extend the useful life of the motors, improve the efficiency of the motors, and reduce the need for new production.

When motors reach the end of their useful life, they should be recycled to recover valuable materials such as copper, aluminium, and steel. This can be facilitated and maximized for example by developing efficient recycling processes and designing motors for easy dismantling, recycling, and recovery. These measures may fall under the recycling strategy.

4.1. Method

The 3R strategy is used to categorize the circular economy measures to have a structured approach. The circular economy measures suggested in Table 6 such as increasing the recycling content, increasing the recyclability, and extending the lifetime of the product are selected. These measures are implemented in the revised EcoReport tool by changing the recycled content (variable R_1 in the simplified CFF) and the recycling output rate (variable R_2 in the simplified CFF) in the raw materials input and extending the lifetime of the product through the increase of reliability, repairability or upgradability level. As noted previously, the share of recycled content and recycling rate for most materials in the current EcoReport tool is directly embedded in the datasets, hence the suggested measures are only implemented in the revised EcoReport tool. An overview of the concept is presented in Figure 13.

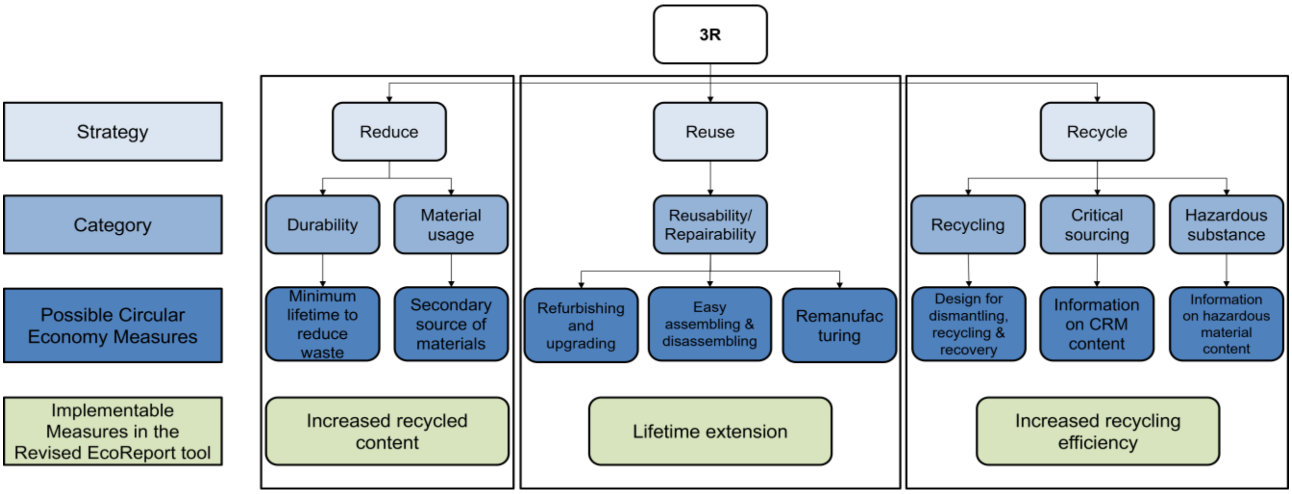


Figure 13: Overview of 3R framework and circular economy measures for electric motors, adopted from [6, 15]

Among the metals in the material bill, copper is more crucial in comparison to aluminium, steel, etc., not to mention that copper windings are commonly changed 2-4 times throughout a motor's lifetime as it is one of the common failing parts [13]. Hence, the assessed circular economy measures for material will be solely implemented on copper. According to the European Copper Institute (personal communication, February 2022), the use of recycled copper in the production of induction motors is around 46% and the copper recycling rate from induction motors is around 42%. The variation of recycled content and recyclability will be based on the provided estimate by the European Copper Institute. The lifetime of the motor is extended by changing the level of reliability, repairability and upgradability in the revised EcoReport tool and the upper limit of the life range is based on the study by Hasanuzzaman et.al [52].

Table 8 presents an overview of the circular economy measures that are implemented on an IE3 1.1 kW induction motor. "All measures" indicates that increasing recycled content, increasing recyclability, and extending the lifetime of the motors are implemented in the revised EcoReport tool, not from summing the results from the individual measures to avoid double counting.

Table 8: Overview of assumed implemented circular economy measures for IE3 1.1 kW induction motors

Circular Economy Measure	**Standard Base Case**	**Increased Recycled Content**	**Increased Recyclability**	**Lifetime Extension**	**All Measures**
Recycled content of copper [%]	30%	50%	30%	30%	50%
Recyclability of copper [%]	40%	40%	60%	40%	60%
Lifetime [years]	12	12	12	15	15

4.2. Results

This subchapter answers the second research sub-question. Table 9 provides the relative percentage difference of the environmental impact results per year across all life cycle stages for an IE3 1.1 kW induction motor with implemented measures compared to the standard base case. The relative percentage difference of the environmental impact varies across different life cycle stages and is detailed in Annex I.

According to Table 9, the implementation of the circular economy measures results in a decrease in the majority of environmental impacts with a few exceptions. Increasing the recycled content and recyclability of copper leads to a decrease in most impact categories, except climate change, ionizing radiation, and resource use. Increasing the recyclability of copper notably reduces the human toxicity and freshwater eutrophication by approximately 23% when compared to the standard base case, while lifetime extension noticeably reduces the impacts related to human toxicity, freshwater eutrophication and minerals and metals use by approximately 20%. The relative percentage difference of the single score impacts (normalized, weighted and aggregated) relating to the implemented circular economy measures compared to the standard base case are presented in the last row of Table 9 as well, to have an idea of the magnitude of the overall change.

The same measures are also applied to IE3 11 kW and IE3 110 kW. The results and comparison analysis can be found in Annex I, and the conclusions drawn from these results are similar to the findings for IE3 1.1 kW motor.

Table 9: Environmental impacts per year of implemented circular economy measures compared to standard base case for IE3 1.1 kW induction motor

Implemented Measure / Impact	Increased Recycled Content of Copper	Increased Recyclability of Copper	Lifetime Extension	All Measures
Climate change	0.0%	0.0%	-6.5%	-6.5%
Ozone depletion	-1.4%	-5.5%	-9.1%	-14.6%
Human toxicity (cancer)	-5.4%	-21.8%	-18.9%	-40.7%
Human toxicity (non-cancer)	-6.0%	-24.0%	-19.4%	-43.4%
Particulate matter	-0.7%	-2.7%	-7.1%	-9.8%
Ionising radiation (human health)	0.1%	0.2%	-4.3%	-4.1%
Photochemical ozone formation (human health)	-1.0%	-4.0%	-7.5%	-11.5%
Acidification	-2.6%	-10.3%	-11.0%	-21.4%
Eutrophication (terrestrial)	-1.0%	-3.8%	-7.4%	-11.2%
Eutrophication (freshwater)	-6.4%	-25.7%	-19.9%	-45.6%
Eutrophication (marine)	-1.3%	-5.2%	-8.0%	-13.3%
Ecotoxicity (freshwater)	-0.2%	-1.0%	-4.7%	-5.6%
Land use	-0.5%	-2.0%	-7.0%	-8.9%
Water use	-0.2%	-0.8%	-5.5%	-6.3%
Resource use (minerals and metals)	0.0%	0.0%	-20.0%	-20.0%
Resource use (fossils)	0.1%	0.5%	-6.4%	-5.9%
Single score impact	-0.5%	-1.8%	-6.9%	-31.6%

4.2.1. Sensitivity Analysis

The allocation factor (A factor) allocates burdens and credits between the supplier and user of recycled materials and aims to represent the market situation [53]. Following the same source, in CFF A = 0.2 indicates that there is a low offer of recyclable materials and high demand, and the formula focuses on the recyclability of the materials. For A = 0.8, the opposite is the case where there is a high offer of recyclable materials and low demand, and the formula focuses on the recycled content of the materials. When A = 0.5, the offer and demand are balanced and the formula focuses on both recycled content and recyclability at EOL [53].

Sensitivity analyses are carried out on the IE3 1.1 kW induction motor, and the results are compared to the standard base case. The recycled content and the recyclability of copper are varied to understand the range of potential outcomes. The default value for the A factor for metals in the revised EcoReport tool is 0.2 and as stated earlier, this indicates that the environmental impact is allocated to the recyclability of the materials at EOL. The A factor for copper is changed to 0.8 so that the environmental impact is allocated to the recycled content of materials, and to examine the effect of the change.

The sensitivity analysis results in Table 10 show that increasing the recycled content and recyclability of copper by 50 % significantly lowers all environmental impacts. On the other hand, changing the allocation factor increases the majority of the environmental impacts due to significantly lower credits in the EOL phase. This indicates that the allocation factor can immensely influence the overall outcomes. It is to note that the use phase is not affected by the sensitivity analysis and hence the changes below do not impact the overall results too much. The relative percentage difference of the single score impacts (normalized, weighted and aggregated) relating to the sensitivity analysis compared to the standard base case are presented in the last row of Table 10 as well, to have an idea of the magnitude of the overall change.

Table 10: Sensitivity analysis results for IE3 1.1 kW induction motor

Sensitivity Analysis / **Impact**	**Recycled Content ($R_{1,copper}$ = 80 %)**	**Recyclability ($R_{2,copper}$ = 90 %)**	**A Factor (A_{copper} = 0.8)**
Climate change	0.0%	-20.0%	0.0%
Ozone depletion	-3.5%	-31.1%	2.1%
Human toxicity (cancer)	-13.6%	-63.6%	8.2%
Human toxicity (non-cancer)	-15.0%	-68.0%	9.0%
Particulate matter	-1.7%	-25.3%	1.0%
Ionising radiation (human health)	0.1%	-19.6%	-0.1%
Photochemical ozone formation (human health)	-2.5%	-27.9%	1.5%
Acidification	-6.5%	-40.7%	3.9%
Eutrophication (terrestrial)	-2.4%	-27.6%	1.4%
Eutrophication (freshwater)	-16.0%	-71.4%	9.6%
Eutrophication (marine)	-3.3%	-30.5%	2.0%
Ecotoxicity (freshwater)	-0.6%	-21.9%	0.4%
Land use	-1.2%	-23.9%	0.7%
Water use	-0.5%	-21.5%	0.3%
Resource use (minerals and metals)	0.0%	-20.0%	0.0%
Resource use (fossils)	0.3%	-19.0%	-0.2%
Single score impact	-1.1%	-4.6%	0.7%

4.3. Summary

In this section, possible circular economy measures that are identified in 3.2 are categorized in the 3R framework to structure the approach. The measures are implemented in the revised EcoReport tool by increasing the recycled content of copper, increasing the recyclability of copper, extending the lifetime of the product, and implementing all the above measures. The implementation of the measures leads to a conservative improvement across most impact categories.

When examining the increasing recycled content and recyclability of copper as well as the A factor further in a sensitivity analysis, increasing the recyclability of copper shows promising environmental improvements. Whereas changing the A factor from 0.2 to 0.8, which signifies focusing the formula on the recycled content instead of the recyclability of copper, presents a slight increase across the majority of environmental impacts. This indicates that the choice of the A factor may influence the outcome of the results.

5. Phase 3: Stock Modelling and Scenario Analysis

To evaluate the long-term effects of the circular economy measures, stock modelling and scenario analysis are carried out. The base cases in the stock modelling and scenario analysis are defined as typical induction motors in the EU market with three different reference output powers 1.1 kW, 11 kW and 110 kW.

5.1. Method

The modelling is a bottom-up, stock-driven approach and is carried out with the following steps:

1. Listing of the scenarios and assumptions.
2. Determining the stock and sales for the years 2000-2050 for three base cases.
3. Determining the long-term effects of the circular economy measures with stock data and environmental implications from the EcoReport tool.

5.1.1. Scenario and Assumption

The overview of scenarios for 1.1 kW induction motors is listed in Table 11. The same scenarios and circular economy measures are applied to IE3 11 kW and 110 kW as well, except they have different average and extended lifetimes. It is assumed that the circular economy measures are policies to be implemented on all new motors sold starting in the year 2025.

Table 11: Overview of scenarios for 1.1 kW induction motors

Scenario / CE Measure	S1 – IE3 Motor	S2 – IE3 Motor with Recycled Content Variation	S3 – IE3 Motor with Recyclability Variation	S4 – IE3 Motor with Lifetime Extension	S5 – IE3 Motor with All CE Measures	S6 – IE4 Motor
Recycled content of copper (%)	30%	50%	30%	30%	50%	30%
Recyclability of copper (%)	40%	40%	60%	40%	60%	40%
Lifetime (years)	12	12	12	15	15	12

5.1.2. Stock and Sales Modelling

The stock and sales for the year 2000-2050 are determined. The term stock here refers to the number of motors currently in operation in the EU market. The stock data for the electric motors is obtained from the Ecodesign Preparatory Study on Lot 11 Motors [13] and is shown in Table 12 per power range. For power ranges 0.75 – 7.5 kW (small motor), 7.5 – 37 kW (medium motor) and >75 kW (large motor), the base models of 1.1 kW, 11 kW and 110 kW were respectively used to represent the data. With the available data, the yearly stocks from 2000 to 2050 are determined through linear interpolation between the known years in Table 12. The resulting yearly stock figures for all base cases can be seen in Figure 14.

Table 12: Total stock for industry and tertiary EU-15 from Ecodesign Preparatory Study on Lot 11 Motors [13]

Stock for Industry and Tertiary EU-15 (in Million Units)	**1992**	**2000**	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**
0.75 – 7.5 kW	61.1	69.8	76.7	84.9	92.0	97.5	102.4	105.5
7.5 – 37 kW	6.8	7.8	8.5	9.4	10.1	10.7	11.2	11.5
37 – 75 kW	1.27	1.45	1.49	1.71	1.82	1.91	1.99	2.04
>75 kW	0.69	0.80	0.85	0.92	0.97	1.01	1.05	1.06

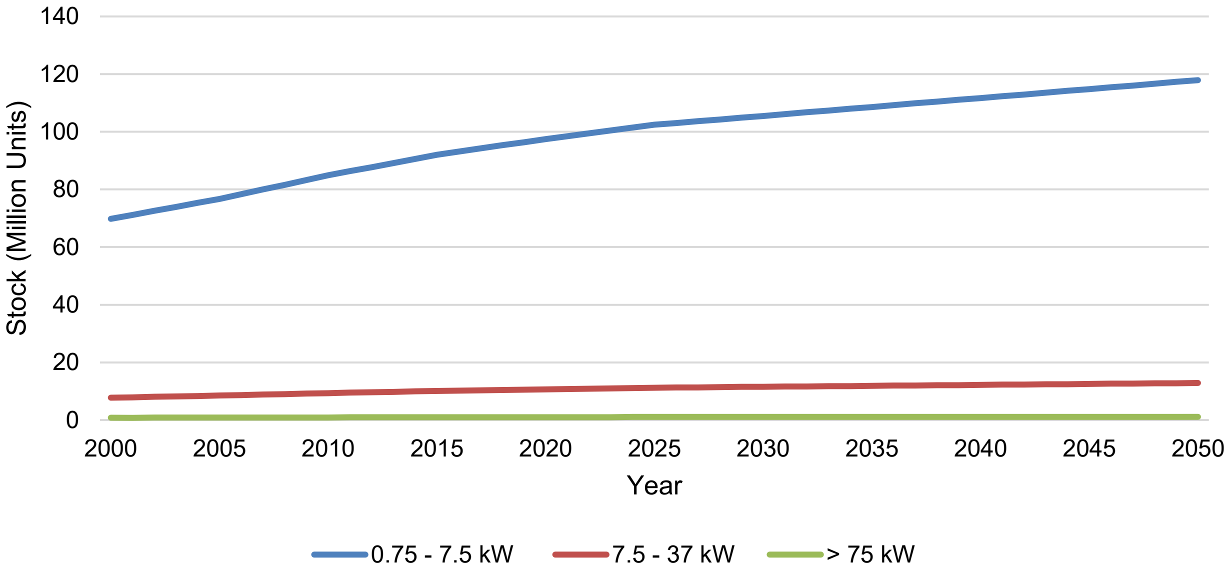


Figure 14: Yearly stock projection for induction motors from 2000 to 2050

The sales figures are calculated based on the stock figures together with the lifetime of the motor using the following equations [54]:

$$sales_{BC_i,y} = stock_{BC,y} - stock_{BC_i,y-1} + sales_{BC_i,y-lifetime_{BC_i}} \tag{2}$$

$$stock_{BC_i,y} = \sum_{j=y-lifetime_{BC_i}+1}^{y} sales_{BC_i,j} \tag{3}$$

Where:

- y = year
- lifetime = lifetime of motor
- BC = base case
- i = index of scenarios

The blue line in Figure 15 represents the projected sales figures for induction motors with an output power of 0.75 – 7.5 kW and a lifetime of 12 years. The red line in Figure 15 on the other hand represents the sales figures of 0.75 – 7.5 kW motors entering the market in 2025, assuming an extended lifetime of 15 years. The sales between 2037 and 2039 show a noticeable drop as indicated by the red line on the graph. This is due to the assumption that the stock stays constant, and with equation (2), the sales in 2037 are calculated by subtracting the stock in 2037 from the stock in the previous year, and then adding the number of motors that reached the end of their lifespan in 2025 to replace them. However, in this case, the motors sold in 2025 will remain in use until 2040 due to their extended lifetime, hence the disparity. This effect is also applied in the year 2038 and 2039.

Sales figures for motors with an output power of 7.5 – 37 kW and >75 kW, along with different lifetimes are provided in Annex II.

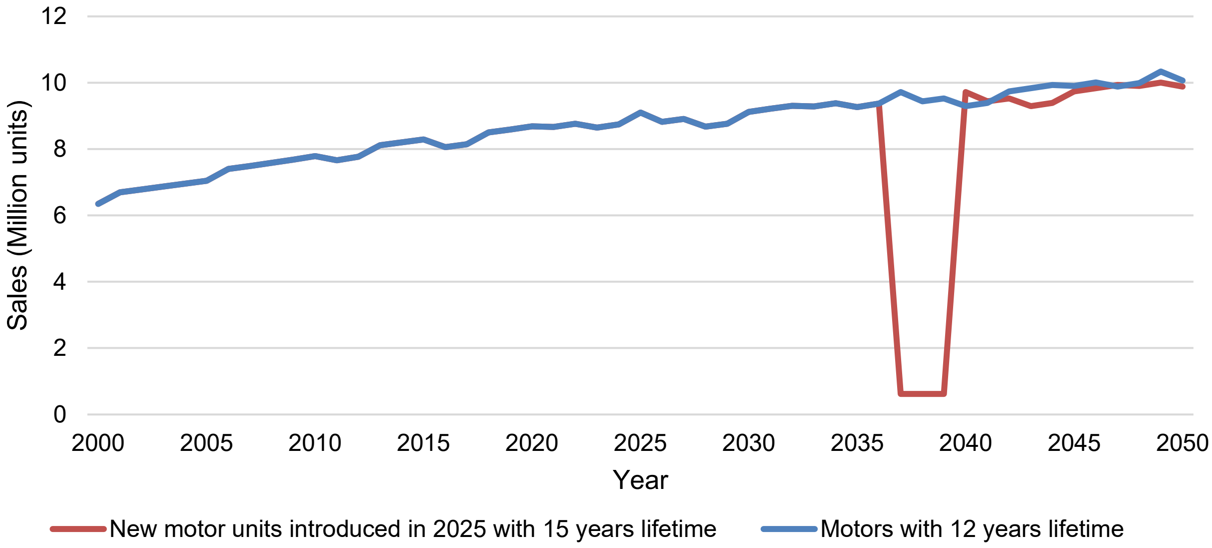


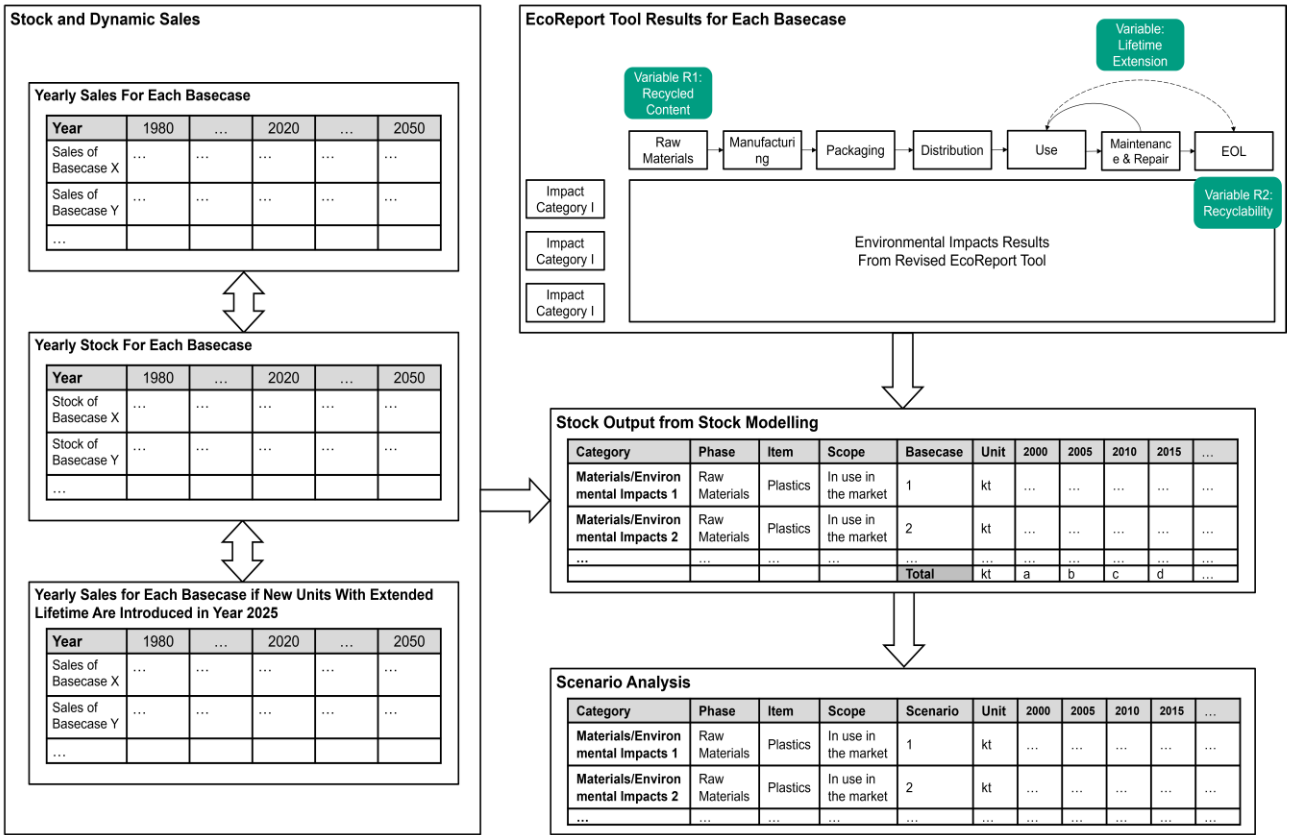
Figure 15: Yearly sales projection for 0.75 – 7.5 kW induction motors from 2000 to 2050

5.1.3. Long-Term Effects Modelling

The stock output is calculated based on the environmental impact results from the revised EcoReport tool, together with the stock and sales data. An overview of the stock modelling approach is presented in Figure 16.

The modelling is carried out with Excel and is designed to be flexible, allowing for the addition of supplementary information such as new base cases, materials, environmental impacts, and phases, all of which will be incorporated into the final calculation and stock output. The stock modelling varies depending on the specific life cycle phases and scenarios being considered. Details of the stock modelling approach can be found in Table A 5 in the Appendix.

Examples of the stock modelling output for materials and environmental impacts in the raw materials phase are shown in Figure A 8 and Figure A 9 . In these figures, it is shown that additional base cases can be added, and the corresponding stock output will be reflected. The complete stock outputs can be found in Annex II.



Yearly Sales For Each Basecase

Year	1980	…	2020	…	2050
Sales of Basecase X	…	…	…	…	…
Sales of Basecase Y	…	…	…	…	…
…					

Yearly Stock For Each Basecase

Year	1980	…	2020	…	2050
Stock of Basecase X	…	…	…	…	…
Stock of Basecase Y	…	…	…	…	…
…					

Yearly Sales for Each Basecase if New Units With Extended Lifetime Are Introduced in Year 2025

Year	1980	…	2020	…	2050
Sales of Basecase X	…	…	…	…	…
Sales of Basecase Y	…	…	…	…	…
…					

Stock Output from Stock Modelling

Category	Phase	Item	Scope	Basecase	Unit	2000	2005	2010	2015	…
Materials/Environmental Impacts 1	Raw Materials	Plastics	In use in the market	1	kt	…	…	…	…	…
Materials/Environmental Impacts 2	Raw Materials	Plastics	In use in the market	2	kt	…	…	…	…	…
…	…	…	…	…	…	…	…	…	…	…
				Total	kt	a	b	c	d	…

Scenario Analysis

Category	Phase	Item	Scope	Scenario	Unit	2000	2005	2010	2015	…
Materials/Environmental Impacts 1	Raw Materials	Plastics	In use in the market	1	kt	…	…	…	…	…
Materials/Environmental Impacts 2	Raw Materials	Plastics	In use in the market	2	kt	…	…	…	…	…
…	…	…	…	…	…	…	…	…	…	…

Figure 16: Overview of the stock modelling approach

5.2. Results

The third research sub-question is answered in this subchapter. Long-term effects of the impacts such as land use, the utilization of fossil, copper consumption, and electricity consumption are chosen to be investigated, as they are identified as the main contributors of the environmental hotspots for the case study of the induction motors, as outlined in Table 6. The projected long-term effects include the EU stock and the impacts of all induction motors in the EU market across all scenarios from 2020 to 2050. The study does not consider replacing IE3 with IE4 motors starting in 2025 as a circular economy measure in Chapter 4, as the main focus is not on improving the energy efficiency of the motor. However, the long-term impact of introducing an IE4 motor in 2025 is also examined in this chapter for comparison. The findings of the analyses are presented in the subsequent subchapters.

5.2.1. Land Use

Figure 17 presents the evolution of the land use impact of induction motors for all life cycle phases per scenario based on EU stock from 2020 to 2050. The IE4 scenario shows a 5% increase in land use impact in 2025, followed by a decrease in the subsequent years until 2040. The best improvement potential by 2050 is observed in the IE3 all measures and IE4 scenarios, where a reduction in land use impact by 4.7 and 10.5 % respectively is seen compared to the IE3 scenario.

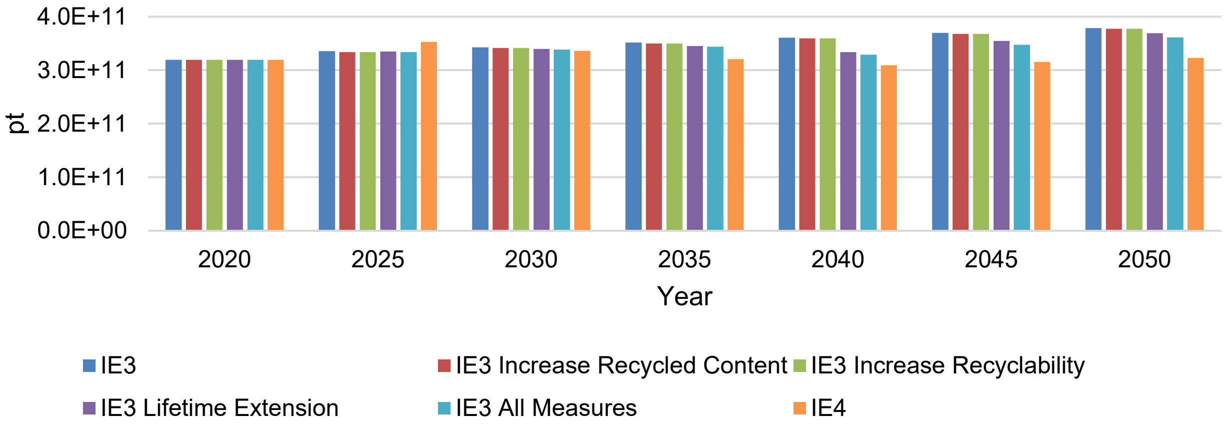


Figure 17: Land use impact of induction motors across all life cycle phases per scenario (EU-15 motor stock)

Table 13 displays the absolute difference, while Table 14 presents the relative percentage difference in the land use impact of the other scenarios compared to the IE3 scenario in 2050. These comparisons are based on the EU stock and are analysed per life cycle phase. Table 13 is shown as the relative percentage difference in Table 14 may be distorted by variations in the magnitudes of impacts across different life cycle phases.

Based on the tables, applying all measures leads to a significant reduction in land use impact due to the decrease in the use phase. The IE4 motor scenario shows an overall increase in land use, particularly in the raw materials, maintenance and repair, and EOL phase, but it has a lower overall land use impact due to the improved energy consumption during the use phase.

Table 13: Absolute difference of land use impact (dimensionless) of induction motors in 2050 (EU-15 motor stock)

	Scenario				
Phase	**IE3 Increased Recycled Content**	**IE3 Increased Recyclability**	**IE3 Lifetime Extension**	**IE3 All Measures**	**IE4**
Raw materials	-1.7E+09	0.0E+00	-1.4E+09	-3.0E+09	1.9E+10
Manufacturing	0.0E+00	0.0E+00	-3.0E+07	-3.0E+07	2.7E+08
Distribution	0.0E+00	0.0E+00	-1.3E+07	-1.3E+07	1.2E+08
Packaging	0.0E+00	0.0E+00	-8.8E+08	-8.8E+08	0.0E+00
Use	0.0E+00	0.0E+00	-8.0E+09	-8.0E+09	-7.1E+10
Maintenance and repair	-1.7E+07	0.0E+00	-1.4E+07	-3.0E+07	1.9E+08
EOL	0.0E+00	-6.3E+09	3.2E+08	-5.8E+09	-4.4E+09
All	-1.7E+09	-6.3E+09	-9.9E+09	-1.8E+10	-4.0E+10

Table 14: Relative percentage difference of land use impact of induction motors in 2050 (EU-15 motor stock)

	Scenario				
Phase	**IE3 Increased Recycled Content**	**IE3 Increased Recyclability**	**IE3 Lifetime Extension**	**IE3 All Measures**	**IE4**
Raw materials	-3.2%	0.0%	-2.6%	-5.8%	36.2%
Manufacturing	0.0%	0.0%	-2.7%	-2.7%	24.7%
Distribution	0.0%	0.0%	-2.8%	-2.8%	25.1%
Packaging	0.0%	0.0%	-3.0%	-3.0%	0.0%
Use	0.0%	0.0%	-2.6%	-2.6%	-23.1%
Maintenance and repair	-3.2%	0.0%	-2.6%	-5.7%	36.0%
EOL	0.0%	52.6%	-2.6%	48.6%	36.4%
All	-0.4%	-1.7%	-2.6%	-4.7%	-10.5%

5.2.2. Resource Use, Fossils

The revised EcoReport defines the impact category of resource use, fossil as the use of non-renewable fossil natural resources. Figure 18 illustrates the evolution of fossil resource use of induction motors in EU stock across all life cycle phases for different scenarios from 2020 to 2050. In the IE4 scenario, fossil use impact is projected to rise by 5% in 2025, but it decreases in the following years until 2040. The best improvement potential in 2050 is observed in the IE3 lifetime extension and IE4 scenarios. The scenarios achieve a reduction in fossil use impact by 2.6 % and 13.9 % respectively when compared to the IE3 scenario.

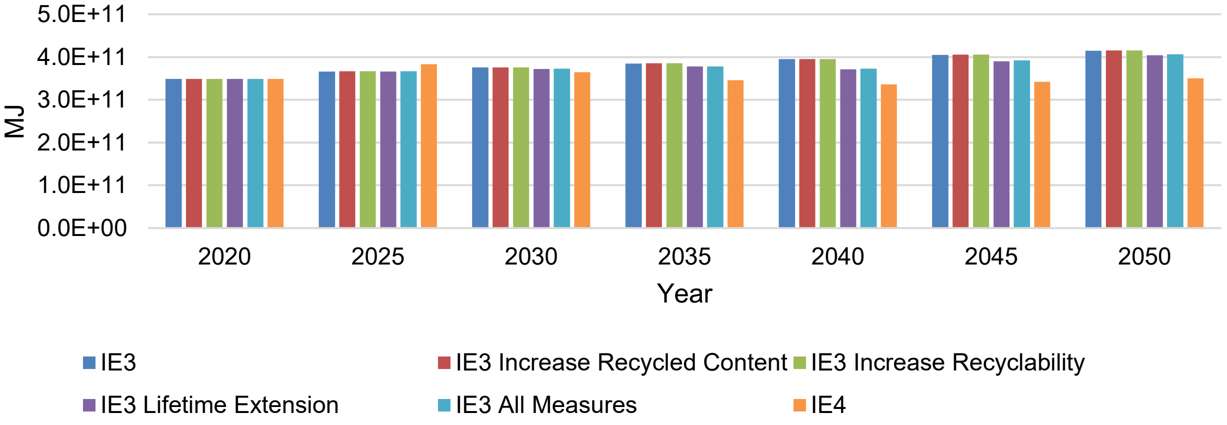


Figure 18: Fossil use impact of induction motors across all life cycle phases per scenario (EU-15 motor stock)

Table 15 displays the absolute difference, while Table 16 presents the relative percentage difference in the fossil use impact of the scenarios compared to the IE3 scenario in 2050. These comparisons are based on the EU stock and analysed per life cycle phase. Table 15 is shown as differences in the magnitudes of impacts across different life cycle phases can distort the relative percentage differences in Table 16.

Based on the tables, increasing the recycled content of copper results in a slightly elevated fossil usage particularly in the raw materials and maintenance and repair phases, whereas increasing the recyclability of copper leads to an increased EOL credit. Implementing all measures did not lead to the desired reduction in fossil use due to the increased consumption of fossils in the IE3 increased recycled content scenario, though this is consistent with the findings in Table 9. IE4 motor scenario on the other hand has an overall increase in fossil use, particularly in the raw materials and maintenance and repair phases. However, this increase is outweighed by the significant improvement in energy consumption during the use phase, resulting in a reduced overall impact on fossil resource usage.

Table 15: Absolute difference of fossil use impact (in MJ) of induction motors in 2050 (EU-15 motor stock)

	Scenario				
Phase	**IE3 Increased Recycled Content**	**IE3 Increased Recyclability**	**IE3 Lifetime Extension**	**IE3 All Measures**	**IE4**
Raw materials	4.6E+08	0.0E+00	-1.4E+09	-9.6E+08	1.6E+10
Manufacturing	0.0E+00	0.0E+00	-3.0E+08	-3.0E+08	1.6E+09
Distribution	0.0E+00	0.0E+00	-2.3E+07	-2.3E+07	2.0E+08
Packaging	0.0E+00	0.0E+00	-3.3E+07	-3.3E+07	0.0E+00
Use	0.0E+00	0.0E+00	-9.2E+09	-9.2E+09	-8.2E+10
Maintenance and repair	4.6E+06	0.0E+00	-1.7E+07	-1.3E+07	1.8E+08
EOL	0.0E+00	1.8E+09	1.6E+08	1.9E+09	-7.8E+08
All	4.7E+08	1.8E+09	-1.1E+10	-8.6E+09	-5.8E+10

Table 16: Relative percentage difference of fossil use impact of induction motors in 2050 (EU-15 motor stock)

	Scenario				
Phase	**IE3 Increased Recycled Content**	**IE3 Increased Recyclability**	**IE3 Lifetime Extension**	**IE3 All Measures**	**IE4**
Raw materials	0.9%	0.0%	-2.7%	-1.8%	30.9%
Manufacturing	0.0%	0.0%	-2.8%	-2.8%	15.5%
Distribution	0.0%	0.0%	-2.8%	-2.8%	25.1%
Packaging	0.0%	0.0%	-3.0%	-3.0%	0.0%
Use	0.0%	0.0%	-2.6%	-2.6%	-23.1%
Maintenance and repair	0.7%	0.0%	-2.7%	-2.0%	28.4%
EOL	0.0%	-29.0%	-2.7%	-30.9%	12.9%
All	0.1%	0.4%	-2.6%	-2.1%	-13.9%

5.2.3. Electricity Consumption

Since electric motors are considered as energy converters with the remaining consumed energy transmitted as mechanical energy to the end-use device, only the energy losses are considered as energy consumed by the motor. The graph in Figure 19 depicts the evolution of electricity consumption of induction motors based on the EU stock during the use phase. Figure 19 illustrates that in 2050, the electricity consumption in the IE4 scenario is significantly lower, approximately 20% below that of the other scenarios.

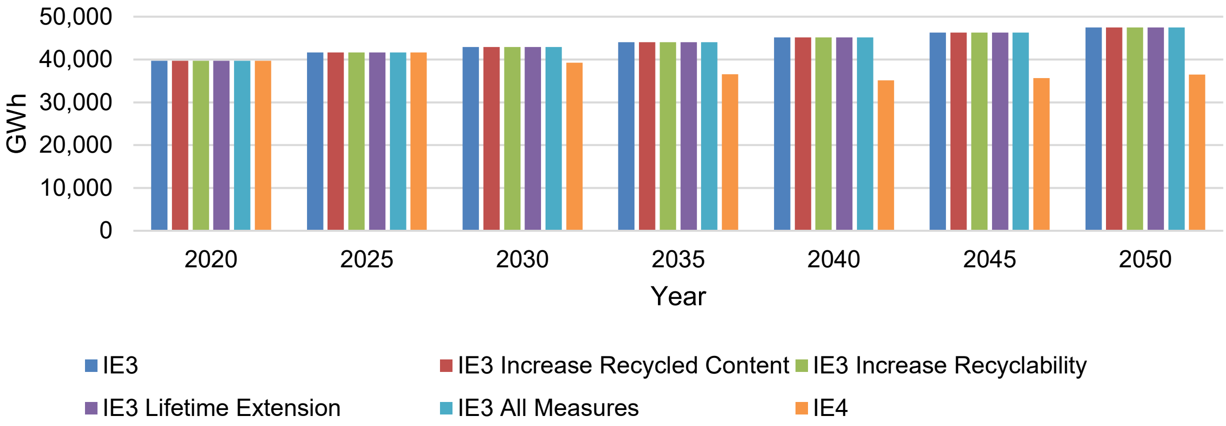


Figure 19: Electricity consumption (energy loss) of induction motors in GWh/year (EU-15 motor stock)

5.2.4. Copper

Figure 20 shows the amount of copper in use during the raw material phase based on EU stock, where the materials remain in use and are unavailable until the end of the motor's lifetime. Figure 21 presents the amount of copper used or allocated for manufacturing and maintenance and repair based on the EU stock. Both figures indicate a consistent upward trend in the copper requirements for induction motors until 2050.

In Figure 20, it is shown that IE4 motors require 35% more copper compared to IE3 motors by the year 2050. Furthermore, the projected amount of copper in use in the raw materials phase is estimated to be 12% higher in 2050 compared to the present (based on year 2025) in the IE3 scenario and 33 % in the IE4 scenario. According to Figure 21, the projected amount of copper required for manufacturing, maintenance and repair in 2050 is anticipated to increase by approximately 9% compared to the amount needed in 2025. While the revised EcoReport tool can incorporate circular economy measures such as increasing the recycled content of copper, the output results do not directly show how the increase in recycled content can reduce the virgin copper demand in the market.

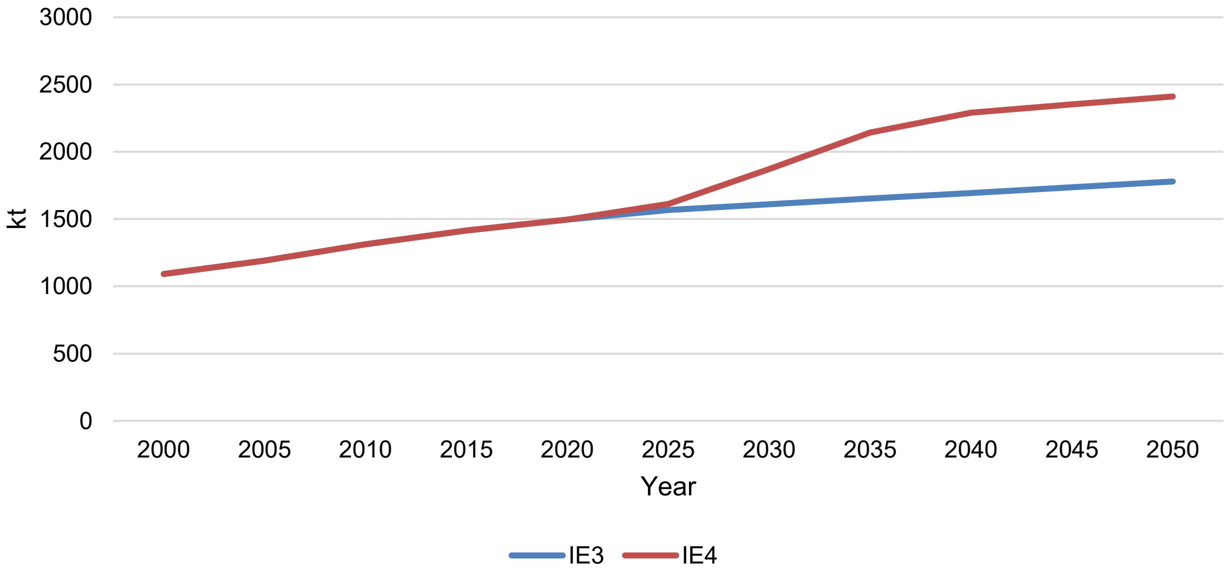


Figure 20: Copper in use in the raw materials phase (EU-15 motor stock)

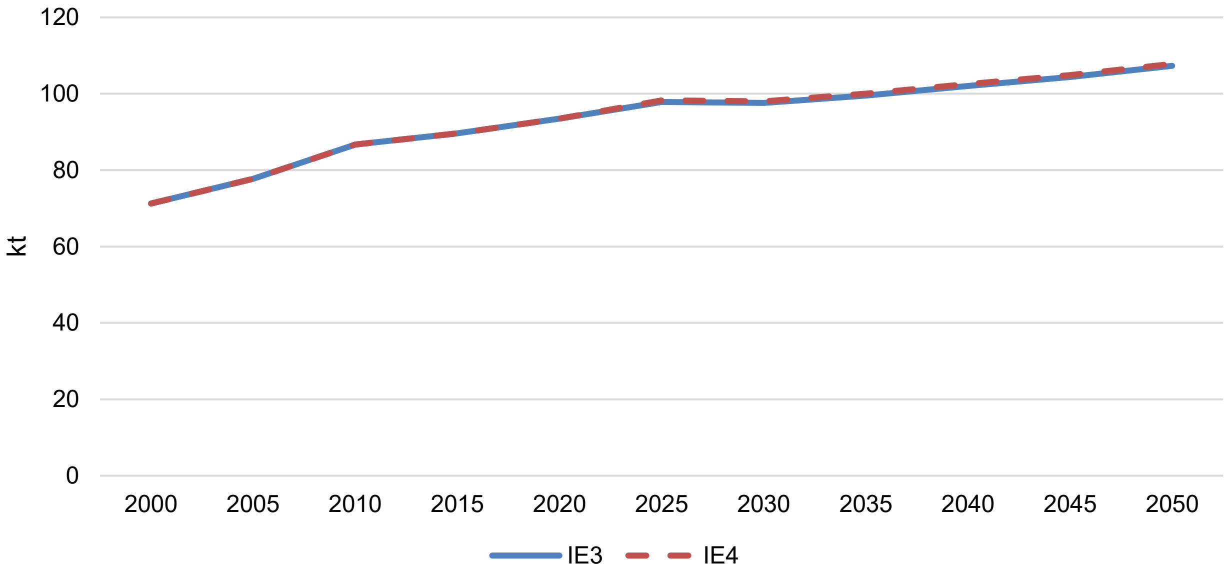


Figure 21: Copper used in manufacturing, maintenance and repair phase (EU-15 motor stock)

5.3. Summary

This section analysed the long-term effect of the circular economy measures for induction motors, assuming that the circular economy measures are implemented on new motor units sold in the year 2025. The long-term effect is evaluated by considering the baseline scenario (scenario without circular economy measures) and the circular economy scenarios (scenarios with the identified measures) and modelling their impacts with the projected stock and sales data in the EU until 2050. The projected scenarios are then compared to understand the potential environmental benefits or trade-offs associated with the circular economy measures and their effectiveness.

For land use and fossil use impact, the circular economy measure which involves extending the lifetime for all new motor units entering the market in 2025 has the highest environmental benefit among the three circular economy measures identified in the 3R framework (see Figure 13). The results also show that by replacing new motor units sold in the year 2025 with IE4 efficiency motors, a significant reduction in land use and fossil use impact can be realized. It is to note that the scenarios that involved increasing the recycled content and recyclability only contribute to a slight reduction in fossil use and land use impact. This is because these measures are only applied to copper, whereas lifetime extension and improved energy efficiency apply to the entire product. Generally, due to the constant increase in stock, the land and fossil use impact have an upward trend from the year 2020 to 2050.

The electricity consumption in the IE4 scenario is lower than the IE3 scenario in 2050 while the copper requirement in the IE4 scenario is higher than in the IE3 scenario. The electricity consumption and copper requirement are projected to increase steadily between 2020 and 2050.

6. Discussion

6.1. Discussion of the Method

The EcoReport tool provides a simple environmental impact assessment for preparatory studies. The structure of the revised EcoReport tool is improved and more intuitive to use, but more guidance could be provided for example on the use of the Weibull lifetime model and the interpretation of the environmental impact results. The revised EcoReport tool was supposed to be finalized and released in 2022, but the release was delayed. Working on the unfinalized revised EcoReport tool did not pose too many issues, apart from having to fix some small bugs.

Most of the necessary input values to calculate the environmental impacts via the revised EcoReport tool were obtained directly from ISR-UC with some assumptions to be made, such as the materials, inputs for manufacturing and the EOL. For example, the material electrical steel was not available in both EcoReport tools, and a close substitute such as a steel sheet is chosen instead. In the revised EcoReport tool, it is possible to add the emission data for electrical steel (an additional material that is not found in the database) and choose it as an input. However, this was not carried out as the datasets in the revised EcoReport tool are dummy values and a comparison might be futile.

Another uncertainty to be noted was the inputs for the manufacturing phase, as the input categories in the current EcoReport tool provided by ISR-UC were different compared to the revised EcoReport tool. The inputs in the revised EcoReport tool for the manufacturing phase were chosen to reflect the ones in the current EcoReport tool as closely as possible. The inputs for the copper’s EOL, namely the recycled content, recyclability and allocation factor were based on the suggestions provided by the European Copper Institute (personal communication, February 2023). The EOL inputs for other materials were the default value in the revised EcoReport tool which were not aligned with the default values from the EF method yet at the time of writing. Further research to ensure the accuracy of the electric motors’ input data was not carried out and hence it is important to note that the inputs for electric motors used in the EcoReport tool in this study were not 100 % accurate. A further important point to consider is that the focus of the Ecodesign Preparatory Study on Lot 11 Motors was on energy efficiency.

PEF normalization and weighting factors were used for the impact assessment to help identify the environmental hotspots. These factors could be advantageous to maintain priority consistency across studies, however, weighting factors should be used with care. In ISO 14044 clause 4.4.3.4, it is mentioned that “Weighting steps are based on value-choices and are not scientifically based. Different individuals, organizations and societies may have different preferences; therefore, it is possible that different parties will reach different weighting results based on the same indicator results”, which indicates that studies with the nature of comparison assertion are not allowed to use results with weighting to avoid bias. In the PEF guide [33], normalization and weighting are optional steps. According to EC (personal communication, February 2023), specific normalization and weighting factors are not planned to be included in the revised EcoReport tool, but pricing for impact categories’ emissions may be introduced as weighting.

The circular economy measures were categorized within the 3R framework for a structured approach. This was beneficial for the organization and to relate the measures to a specific principle. However, more steps could be taken with this approach for example using the framework to suggest a logical sequential implementation of the measures or emphasize which measures should be prioritized. The level of effectiveness of the measures could be also assessed by for example classifying them in a discrete-step scoring system to rank their prospect.

The stock model is currently flexible to take on additional data and is dynamic to reflect the input in the output results. However, more adjustments have to be made to model a scenario such as replacing a certain percentage of inefficient motors in the stock before EOL with high-efficiency motors. In this study, the only assumption that affects the sales is the motor's lifetime. However, incorporating dynamic changes in sales, such as considering the probability of obsolescence, could be a valuable factor to include. Simple sales and stock modelling results are obtainable from both EcoReport tools, with the current EcoReport tool using constant sales and stock and the revised EcoReport tool adopting dynamic sales and stock modelling.

6.2. Discussion of the Results

6.2.1. EcoReport Tool

The hotspot analysis conducted using both EcoReport tools yielded similar conclusions, where both tools identified the use phase of the motor as the primary source of environmental impacts, with copper and electricity identified as the main contributors. However, there are differences in the methods and impact categories. Thus the identified environmental hotspots in both EcoReport tools are different, where electricity is the top hotspot in the current EcoReport tool and land use is the main hotspot in the revised EcoReport tool. Several earlier environmental impact assessment studies on electric motors [46, 55, 56] utilizing the EcoReport tool also consistently demonstrate that the use phase contributes the most significant environmental impact.

The results from the current EcoReport tool are normalised against the share of EU totals, using electricity as the basis for normalisation since it has the highest share. Even though total energy includes electricity and other energy carriers, it did not represent the highest share, but this could be due to the way the EU totals for electricity were calculated. Based on Table A 2, electricity is converted to terawatt-hours for the EU totals and uses a different reference compared to the total energy.

It is surprising to find that land use impact is identified as a significant hotspot for induction motors based on the revised EcoReport tool results, though this could be partly due to the dummy values in the revised EcoReport tool database. This aspect is examined and according to a study by Auer and Anna from 2018 [57], the top three environmental hotspots of a 110 kW nominal power induction motor from the LCA results identified were ionizing radiation, fossil and mineral depletion and GWP, but land use was not investigated. GWP and ionizing radiation ranked fourth and fifth respectively in this study’s environmental hotspot analysis, which indicates a difference in results. However, it is important to note that environmental impact assessment results can vary depending on the specific methodology, system boundaries, and data used in the assessment, hence a one-to-one comparison of the hotspots from both studies should be carried out with caution.

Upon further investigation, the land use impact in the revised EcoReport tool results seems to stem mainly from the raw material and use phases, more specifically from copper extraction and electricity consumption. According to the PEF guide [33], direct land use is defined as “the results of a transformation from one land use type into another, possibly incurring changes in the carbon stock of that specific land”. The extraction of copper may have significant land use impacts as mining activities can result in habitat destruction, soil degradation, deforestation, or displacement of local communities. The impact of electric consumption may be associated with the source of electricity generation or the construction and operations of power plant infrastructure that may require land use and land conversion. Further evaluation will be required to gain a more comprehensive understanding of the specific factors driving the land use impact hotspot in the results.

The revised EcoReport tool not only allows for the identification of environmental hotspots beyond energy consumption but also provides insights into resource consumption. For instance, Figure 10 highlights that human toxicities and freshwater eutrophication impacts are primarily associated with the raw materials phase. This could potentially provide assessments on resource requirements.

However, the normalized and weighted results as seen in Figure 11 suggest that these environmental impacts may not be significant.

Since copper and electricity are identified as the main contributors from both EcoReport tools' results, implementing specific circular economy measures for copper and electricity could lead to saving potentials, through for example potential resource savings and reduced emissions from electricity production with renewable energy. However, the exact magnitude of these savings cannot be directly assessed using the EcoReport tools alone. Additional analyses are necessary to quantify the potential savings and evaluate the environmental and economic benefits associated with these measures. These further assessments will provide a more comprehensive understanding of the potential benefits that can be derived from the implementation of circular economy measures.

In Figure 12, it is interesting to note that for most materials in the BOM, the default recyclability percentage is chosen as 90 % in the revised EcoReport tool. However, the compensation from recycling in the EOL stage is relatively small compared to the raw material and manufacturing phase. A quality check on the simplified CFF approach for the EOL modelling may be worthwhile.

6.2.2. Circular Economy Measures

The current EcoReport tool does not adequately address resource consumption. For example, the average recycling rates are fixed within the material datasets, making it difficult to investigate the specific benefits of using recycled materials. The revised EcoReport tool on the other hand incorporates a more comprehensive representation of resource consumption which involve allowing users to modify recycling rates and evaluating the environmental benefits associated with using recycled materials. This could potentially enable more robust assessments of circular economy measures and their potential effects on resource utilization.

The impacts of the circular economy measure on an individual product level can be assessed using the revised EcoReport tool. With the systematic inclusion of material efficiency aspects in the revised EcoReport tool, measures such as increased durability, increased recyclability, and increased share of secondary raw materials are possible to be incorporated. The environmental impact improvements achieved for each individual product can then be compared and evaluated.

Increasing the recycled content and recyclability of copper by 20% resulted in an overall decrease in environmental impact across all life cycle stages. Specifically, increasing the recyclability of copper showed a greater environmental gain. However, it is worth noting that recycling is considered less favourable in the 3Rs hierarchy. Additionally, extending the product's lifetime proved highly beneficial in reducing environmental impacts. Although lifetime extension generally provides better environmental benefits overall, it is crucial to acknowledge that lifetime extension affects all materials involved, whereas the measures increasing recycled content and recyclability in this study only apply to copper.

The realistic value range for the increase in recycled content and recyclability of copper could be improved based on additional data collection or expert opinions. The specific factors contributing to the increase in the durability of the product, such as the availability of spare parts that increased the ease of upgradability, an increase in reliability due to higher quality materials, or an improvement in overall design for disassembly or repair, are not extensively researched in this study.

6.2.3. Stock Modelling and Scenario Analysis

Based on Figure 17 and Figure 18, the IE4 motor scenario has a higher impact in 2025 due to the higher material composition of the IE4 induction motor. However, over the years the impact from this aspect is compensated by the energy savings from the higher efficiency motor. According to Figure 17 and Figure 18, scenarios where the lifetime of the motor is extended, and all measures are applied also resulted in a decrease in impact over the years when compared to the IE3 scenario. It is important to point out that the environmental benefit from the increasing recycled content and recyclability scenarios are significantly smaller, as these measures were only applied to copper.

The best measure among the investigated circular economy measures is the lifetime extension and the full savings potential can be achieved by implementing all measures. The scenario analysis also indicates that the IE4 motor scenario demonstrates a higher potential for improving the environmental impact in the selected impact categories compared to the IE3 scenarios with the circular economy measures. Only copper requirement is higher in the IE4 scenario compared to the IE3 scenarios, but material requirements are more of a value chain or resource issue. Based on the results, it can be concluded that implementing all circular economy measures in an IE4 scenario offers the greatest potential for environmental impact savings. Hence, the comparison of IE3 and IE4 motors with all circular economy measures may be useful to carry out. It is also crucial to consider the IE3 motor with other alternative circular economy measures. For example, the trade-off between keeping a motor with a longer lifetime and replacing it with a more efficient motor, or new motors with better design for assembly and disassembly.

Circular economy measures, particularly those focused on the EOL stages often require a longer time frame to observe their effects. For example, the 110 kW induction motor has an average lifespan of 20 years. The benefits of circular economy measures implemented during the EOL stage will only become apparent when these replacement cycles occur. Realistically, circular economy measures such as recycling infrastructure may take time to be fully implemented and widely adopted across various industries. It requires building the necessary infrastructure and establishing effective collection and recycling systems. The gradual implementation and adoption of these measures can delay the visible effects. Achieving the optimal material recovery and reuse in the EOL stage is also complex. Recovered materials may need to undergo sorting, treatment, and quality checks before they can be reintroduced into the production cycle. Developing efficient and scalable technologies for material recovery and establishing robust supply chains for recycled materials can take time. The successful implementation of circular economy measures for motors also relies heavily on the proactive involvement and commitment of original equipment manufacturers (OEMs).

Another important point to consider is that the future projection of emission data is not taken into account by the EcoReport tool or the stock modelling. This could be an interesting aspect to consider as the decrease of impacts from the increased use of renewable energy is foreseeable in the future. Stock modelling is not covered or planned in the revised EcoReport tool.

6.3. General Discussion

As the BOM for the induction motor in the EcoReport tool is not too elaborate, it is inconclusive from this study if the updated database is better and more representative of an average EU product. The CRM aspects of the EcoReport tools were also not investigated as the BOM of the induction motors does not consist of magnets. It is also uncertain if the impact categories in the revised EcoReport tool are integrated well with the impact categories in the current EcoReport tool. To begin with, the impact categories have different indicators and units, and they are intended for different goals. According to the draft report on the Review of the MEErP [28], the adoption of the PEF impact categories was driven in part by the objective to harmonise the impact assessment methods and the availability of these established indicators that were ready for implementation.

There are few active EOL requirements or best EOL practices for induction motors [6]. The decision on how to handle the EOL of electric motors often depends on economic considerations. They can either be shredded or manually disassembled, with the choice of process impacting the rate of material recovery. The circularity of electric motors seems to suffer from early stages decisions such as complex disassembly processes or a lack of methodology for selecting the best EOL scenario [6].

Perhaps a methodology for selecting and configuring circular economy strategies in an early design stage proposed by Benfer et al. [57] can be useful.

A quality check on the EcoReport tool results may be performed by comparing the major hotspots from the impact assessment results from the conventional LCA method. However, such quality checks and comparisons of results have to be carried out with the simplicity of calculation methods of the EcoReport tools in mind, as the EcoReport tool is primarily utilized for policy-making processes rather than purely scientific purposes.

7. Conclusion

The objective of this study is to identify circular economy measures for product policies and assess their environmental impacts for the case study of electric motors in the EU. The study found that the EcoReport tools are reliable in quickly identifying environmental impact hotspots throughout the different life cycle stages. However, it is more challenging to pinpoint specific environmental hotspots per impact category without the use of normalization and weighting factors. Nonetheless, the results from the EcoReport tools provide sufficient insights into the key factors driving significant environmental impacts and help identify areas where circular economy measures can have the most substantial effect to support the policy-making process. It is also established that the revised EcoReport tool presents more opportunities to quantify the potential savings of circular economy measures, as it has the capability to assess the aspect of resource consumption. While in-depth knowledge of LCA and an understanding of the complex calculations behind the EcoReport tool is not necessary to utilize and comprehend the tool, additional guidance on certain aspects would enhance its usability.

The impacts of circular economy measure on induction motors in the EU are evaluated using long-term stock modelling. The findings can provide insights for deriving policies concerning new products entering the market in 2025. Further assessment should be conducted by considering alternative circular economy measures and incorporating dynamic sales and stocks. The influence of the dummy values on the final results remains uncertain and will only be determined once the finalized version of the revised EcoReport tool is released.

Transitioning towards a circular economy requires a shift in policy framework, business practices and stakeholder engagement. It requires time to change attitudes, raise awareness, and establish a culture of circularity. As society becomes more conscious of sustainable consumption and production practices, the impact of circular economy measures becomes more apparent. This applies to various sectors, including the induction motor industry in the EU.

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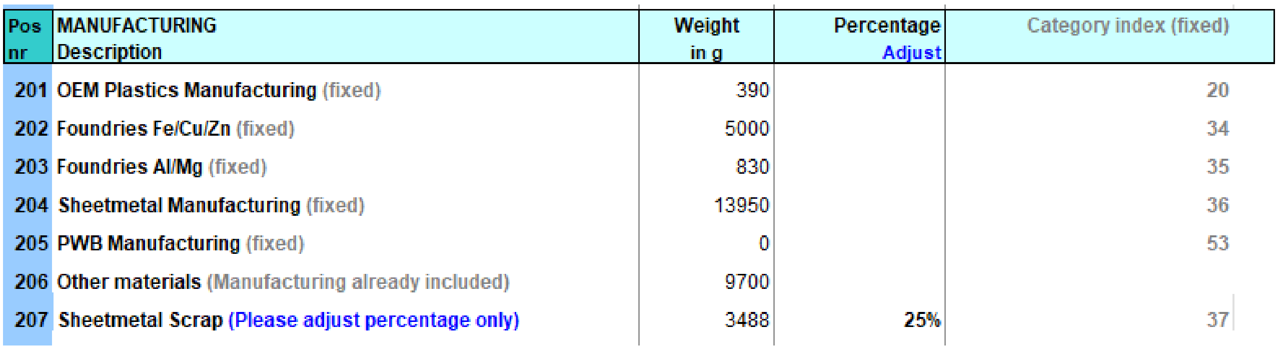
Appendix

A. Supplementary Figures for Chapter 2.3 Current and Revised EcoReport Tools



Pos nr	MANUFACTURING Description	Weight in g	Percentage Adjust	Category index (fixed)
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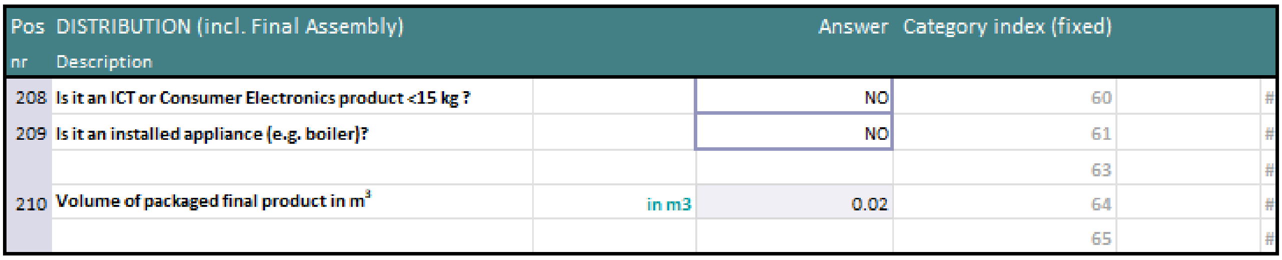
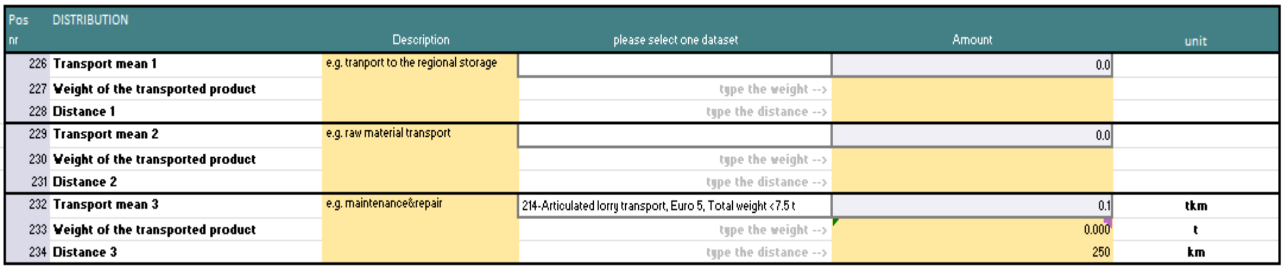
202	Foundries Fe/Cu/Zn (fixed)	5000		34
203	Foundries Al/Mg (fixed)	830		35
204	Sheetmetal Manufacturing (fixed)	13950		36
205	PWB Manufacturing (fixed)	0		53
206	Other materials (Manufacturing already included)	9700		
207	Sheetmetal Scrap (Please adjust percentage only)	3488	25%	37

Figure A 1: Manufacturing section in the current EcoReport tool



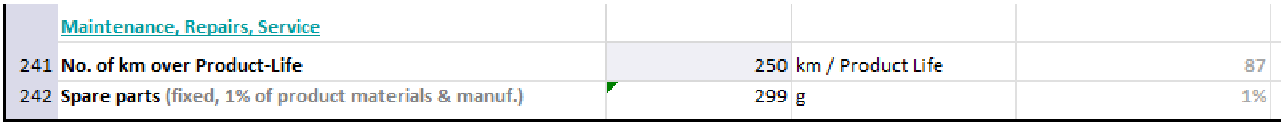
Pos nr	DISTRIBUTION (incl. Final Assembly) Description		Answer	Category index (fixed)	
208	Is it an ICT or Consumer Electronics product <15 kg ?		NO	60	#
209	Is it an installed appliance (e.g. boiler)?		NO	61	#
				63	#
210	Volume of packaged final product in m^3	in m3	0.02	64	#
				65	#

Figure A 2: Distribution section of the current EcoReport tool



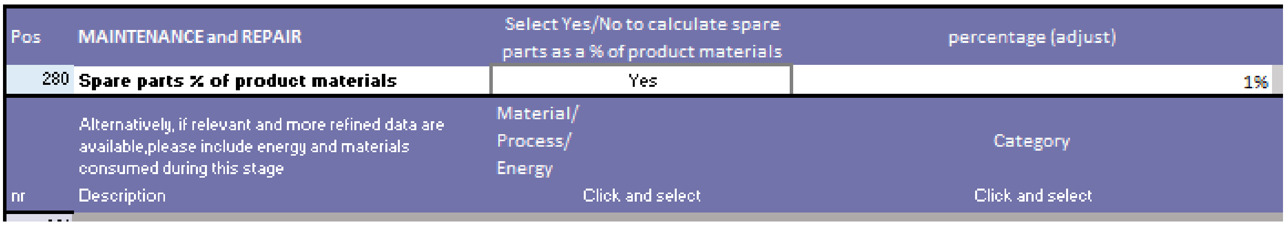
Pos nr	DISTRIBUTION	Description	please select one dataset	Amount	unit
226	Transport mean 1	e.g. tranport to the regional storage		0.0	
227	Weight of the transported product		type the weight -->		
228	Distance 1		type the distance -->		
229	Transport mean 2	e.g. raw material transport		0.0	
230	Weight of the transported product		type the weight -->		
231	Distance 2		type the distance -->		
232	Transport mean 3	e.g. maintenance&repair	214-Articulated lorry transport, Euro 5, Total weight <7.5 t	0.1	tkm
233	Weight of the transported product		type the weight -->	0.000	t
234	Distance 3		type the distance -->	250	km

Figure A 3: Distribution section of the revised EcoReport tool



	Maintenance, Repairs, Service			
241	No. of km over Product-Life	250	km / Product Life	87
242	Spare parts (fixed, 1% of product materials & manuf.)	299	g	1%

Figure A 4: Maintenance and repair section of the current EcoReport tool



Pos	MAINTENANCE and REPAIR	Select Yes/No to calculate spare parts as a % of product materials	percentage (adjust)
280	Spare parts % of product materials	Yes	1%
nr	Alternatively, if relevant and more refined data are available,please include energy and materials consumed during this stage Description	Material/ Process/ Energy Click and select	Category Click and select

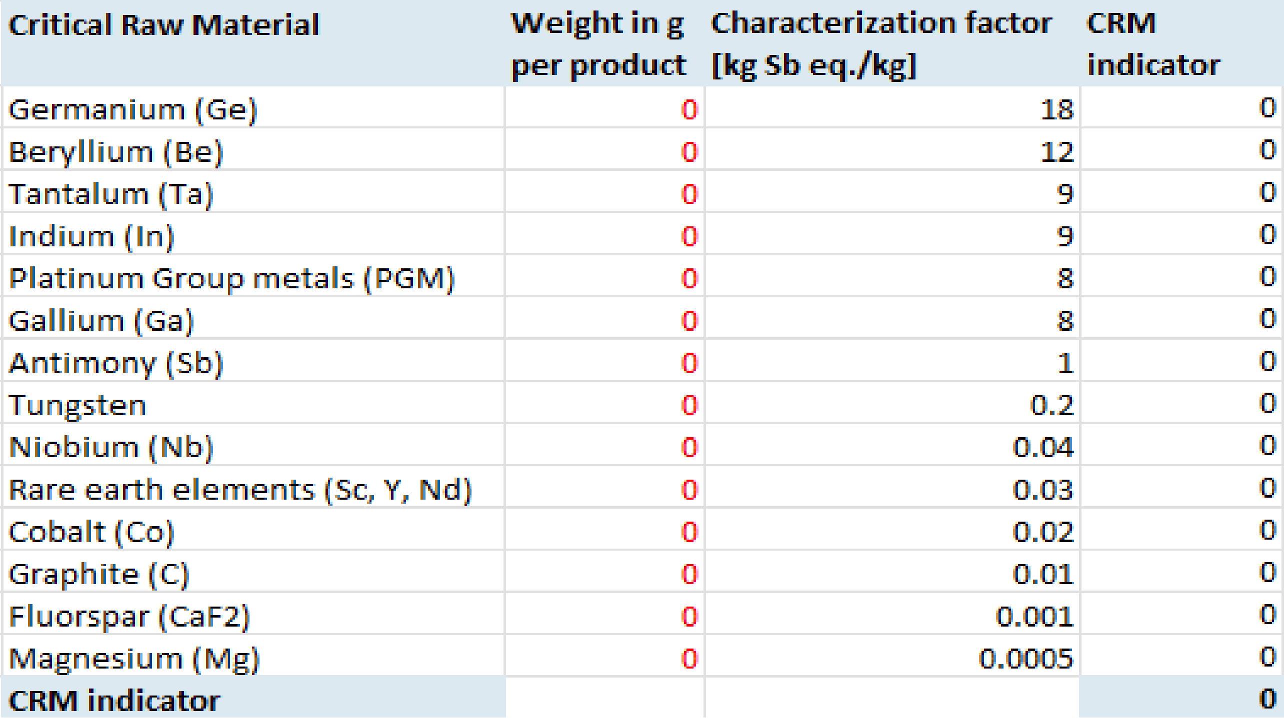
Figure A 5: Maintenance and repair section of the revised EcoReport tool

Table A 1: EcoReport tools CRM list comparison

Current EcoReport Tool: CRM indicator according to MEErP 2011
Critical Raw Material:
Germanium (Ge)
Beryllium (Be)
Tantalum (Ta)
Indium (In)
Platinum Group metals (PGM)
Gallium (Ga)
Antimony (Sb)
Tungsten
Niobium (Nb)
Rare earth elements (Sc, Y, Nd)
Cobalt (Co)
Graphite (C)
Fluorspar (CaF2)
Magnesium (Mg)

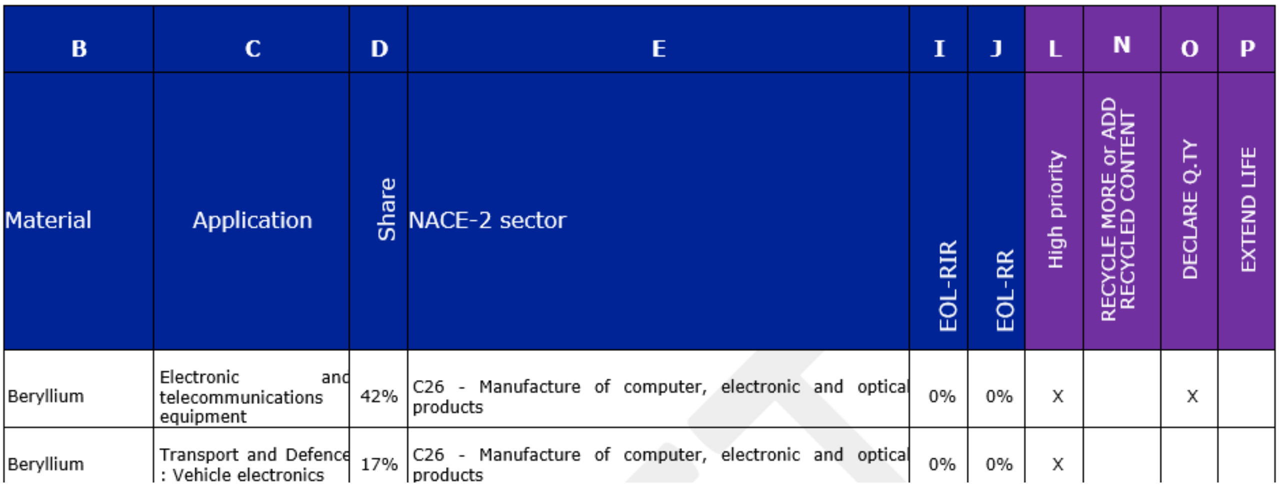
Revised EcoReport Tool: 2020 CRM Assessment	
Material:	**Application:**
Beryllium	Electronic and telecommunications equipment
Beryllium	Transport and Defence: Vehicle electronics
Cobalt	Magnets
Cobalt	Battery
Dysprosium	Magnets
Erbium	Lighting
Europium	Lighting
Fluorspar	Refrigeration and air conditioning
Gadolinium	Magnets
Gadolinium	Lighting
Gadolinium	Magnetic Resonance Imaging - MRI
Gallium	Integrated circuits
Gallium	Lighting
Gallium	CIGS solar cells
Germanium	Infrared optics
Germanium	Optical fibres
Germanium	Satellite solar cells
Ho, Tm, Lu, Yb	Glass - Optical applications
Indium	Flat panel displays
Indium	Solders
Indium	PV cells
Iridium	Electronics
Lanthanum	Batteries
Lanthanum	Lighting
Lithium	Batteries and products containing batteries
Natural graphite	Batteries
Neodymium	Magnets
Neodymium	Batteries
Palladium	Electronics
Platinum	Medical and Biomedical

Platinum	Electronics
Praseodymium	Magnets
Praseodymium	Batteries
Rhodium	Electronics
Ruthenium	Electronics
Samarium	Magnets
Scandium	Solid Oxide Fuel Cells (SOFCs)
Strontium	Magnets
Tantalum	Capacitors
Tantalum	Sputtering targets
Terbium	Lighting
Terbium	Magnets
Titanium	Medical equipment
Tungsten	Lighting and electronic uses
Yttrium	Lighting



Critical Raw Material	Weight in g per product	Characterization factor [kg Sb eq./kg]	CRM indicator
Germanium (Ge)	0	18	0
Beryllium (Be)	0	12	0
Tantalum (Ta)	0	9	0
Indium (In)	0	9	0
Platinum Group metals (PGM)	0	8	0
Gallium (Ga)	0	8	0
Antimony (Sb)	0	1	0
Tungsten	0	0.2	0
Niobium (Nb)	0	0.04	0
Rare earth elements (Sc, Y, Nd)	0	0.03	0
Cobalt (Co)	0	0.02	0
Graphite (C)	0	0.01	0
Fluorspar (CaF2)	0	0.001	0
Magnesium (Mg)	0	0.0005	0
CRM indicator			**0**

Figure A 6: Current EcoReport tool CRM characterization factor



B	C	D	E	I	J	L	N	O	P
Material	Application	Share	NACE-2 sector	EOL-RIR	EOL-RR	High priority	RECYCLE MORE or ADD RECYCLED CONTENT	DECLARE Q.TY	EXTEND LIFE
Beryllium	Electronic and telecommunications equipment	42%	C26 - Manufacture of computer, electronic and optical products	0%	0%	X		X	
Beryllium	Transport and Defence : Vehicle electronics	17%	C26 - Manufacture of computer, electronic and optical products	0%	0%	X			

Figure A 7: Example of short-listed CRMs and specific application derived from the criticality assessment

B. Supplementary Information for Chapter 3.2 Results

Table A 2: Summary of environmental impacts EU-stock 2011

Impacts/Life Cycle Phases		**Production**	**Distribution**	**Use**	**EOL**	**Total**	**% EU Total**
Total energy (GER)	PJ	18.09	0.64	204.94	1.03	224	0.297%
Electricity	TWh	0.21	0.00	22.33	0.00	23	0.805%
Water (process)	mln.m3	1.38	0.00	13.41	0.00	15	0.006%
Waste, non-haz.	Mt	1.60	0.00	0.25	0.01	1.86	0.063%
Waste, haz.	kton	0.00	0.00	0.00	0.00	0.01	0.009%
Emissions (Air)							
GHG	mt CO2 eq.	1.12	0.05	9.08	0.08	10	0.204%
Acidification	kt SO2 eq.	23.65	0.14	52.23	0.15	76	0.339%
VOC	kt	0.03	0.00	0.14	0.00	0	0.002%
POP	g i-Teq.	3.73	0.00	1.35	0.10	5	0.234%
Heavy metals	ton Ni Teq.	7.30	0.03	4.34	0.30	12	0.203%
PAHs	ton Ni Teq.	0.51	0.03	1.23	0.00	2	0.129%
PM, dust	kt	1.35	0.56	15.21	1.33	18	0.524%
Emissions (Water)							
Heavy metals	ton Hg/20	2.29	0.00	1.31	0.09	4	0.029%
Eutrophication	kt PO4	0.10	0.00	0.01	0.00	0	0.012%

Table A 3: Percentage of the use phase impacts considering only losses in the current EcoReport tool

Impact	**Motor Rated Power**		
	1.1 kW	**11 kW**	**110 kW**
Total energy (GER)	93.05%	93.98%	94.74%
Of which electricity	99.28%	99.34%	99.37%
Water (process)	92.51%	92.74%	92.79%
Water (cooling)	99.60%	99.71%	99.77%
Waste, non-hazardous	16.21%	19.09%	22.52%
Waste, hazardous	66.24%	78.11%	83.03%
Emission to air			
GHG	90.38%	91.39%	92.24%
Acidification	73.58%	77.50%	81.18%
VOC	84.24%	76.85%	74.83%
POP	30.91%	32.12%	32.94%
Heavy metals	42.04%	40.79%	42.75%
PAHs	74.42%	61.52%	61.61%
PM, dust	85.67%	56.70%	35.74%
Emissions to water			
Heavy metals	41.32%	42.90%	43.96%
Eutrophication	8.12%	9.65%	10.96%

Table A 4: Percentage of the use phase impacts considering only losses in the revised EcoReport tool

Impact	**Motor Rated Power**		
	1.1 kW	**11 kW**	**110 kW**
Climate change	86.16%	87.31%	88.30%
Ozone depletion	70.62%	72.01%	73.04%
Human toxicity (cancer)	7.93%	9.51%	11.38%
Human toxicity (non-cancer)	4.04%	4.90%	5.95%
Particulate matter	82.50%	85.01%	87.24%
Ionising radiation (human health)	98.39%	98.63%	98.84%
Photochemical ozone formation (human health)	80.22%	82.83%	85.24%
Acidification	59.16%	63.86%	68.42%
Eutrophication (terrestrial)	80.91%	83.42%	85.68%
Eutrophication (freshwater)	0.52%	0.64%	0.79%
Eutrophication (marine)	77.09%	80.09%	82.85%
Ecotoxicity (freshwater)	96.29%	96.88%	97.43%
Land use	83.37%	82.45%	84.81%
Water use	91.63%	91.42%	91.14%
Resource use (minerals and metals)	0.00%	0.00%	0.00%
Resource use (fossils)	86.54%	87.81%	88.85%

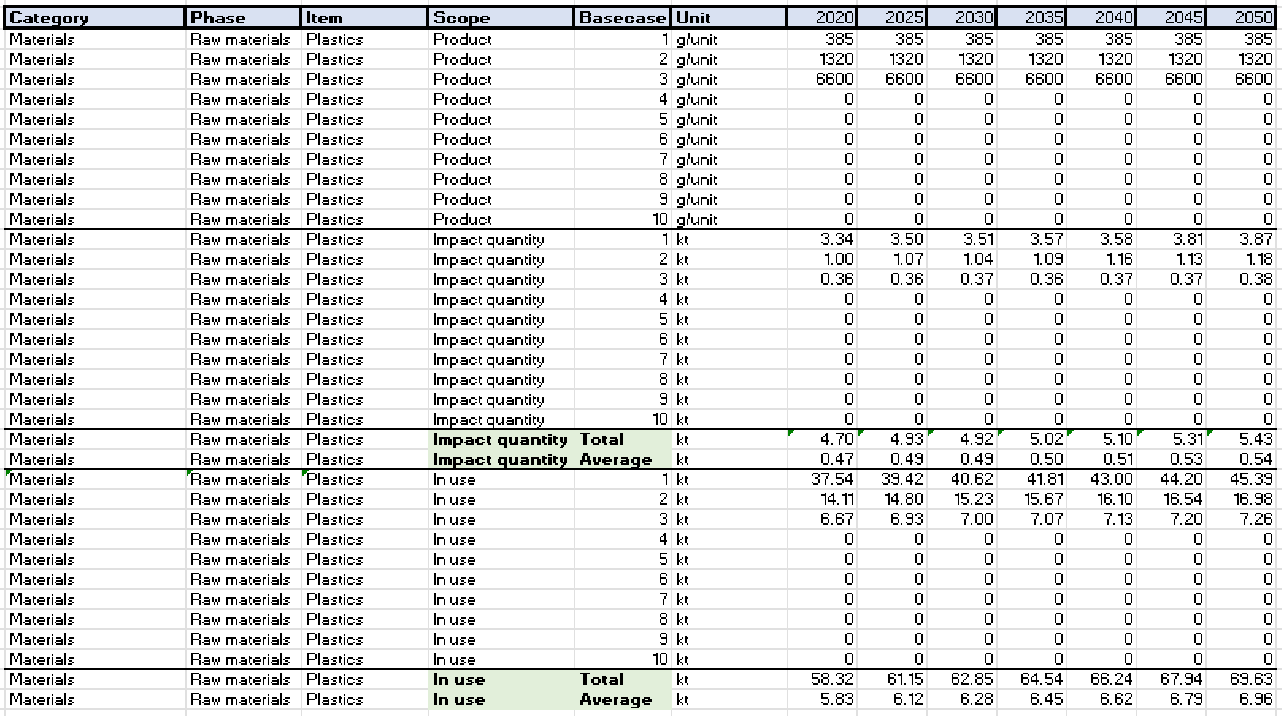
C. Supplementary Information for Chapter 5.1 Method

Table A 5: Stock modelling approach for different phases and types of impacts

Stock Modelling / Life Cycle Phase	Material	Environmental Impact
Raw materials	"In use" in the market until product's lifetime is up. <u>Stock calculation:</u> Impact quantity (y) = Material (y) * Sales (y) Material "in use" (y) = Sum of impact quantity (y-lifetime+1) to impact quantity (y)	Immediately "entered the market" at the beginning of product's lifetime. <u>Stock calculation</u>: Impact per product (y) * Sales (y) = Environmental impact "entered the market" (y)
Manufacturing	Immediately "used" at the beginning of product's lifetime. <u>Stock calculation:</u> Material per product (y) * Sales (y) = Material "used" (y)	Immediately "entered the market" at the beginning of product's lifetime. <u>Stock calculation</u>: Impact per product (y) * Sales (y) = Environmental impact "entered the market" (y)
Distribution	Results from the revised EcoReport tool do not provide output on material distribution, hence is not calculated for stock modelling.	Immediately "entered the market" at the beginning of product's lifetime. <u>Stock calculation</u>: Impact per product (y) * Sales (y) = Environmental impact "entered the market" (y)
Packaging	"In use" in the market until product's lifetime is up. <u>Stock calculation:</u> Impact quantity (y) = Material (y) * Sales (y) Material "in use" (y) = Sum of impact quantity (y-lifetime+1) to impact quantity (y)	Immediately "entered the market" at the beginning of product's lifetime. <u>Stock calculation</u>: Impact per product (y) * Sales (y) = Environmental impact "entered the market" (y)
Use - Energy - "Consumable" materials	"Used" yearly until the end of product's lifetime. <u>Stock calculation:</u> Material "used" (y) = [Material (y) * (Sum of sales (y-1) to	Impacts occur yearly until the end of product's lifetime. <u>Stock calculation:</u> Environmental impact "entered the market" (y) =

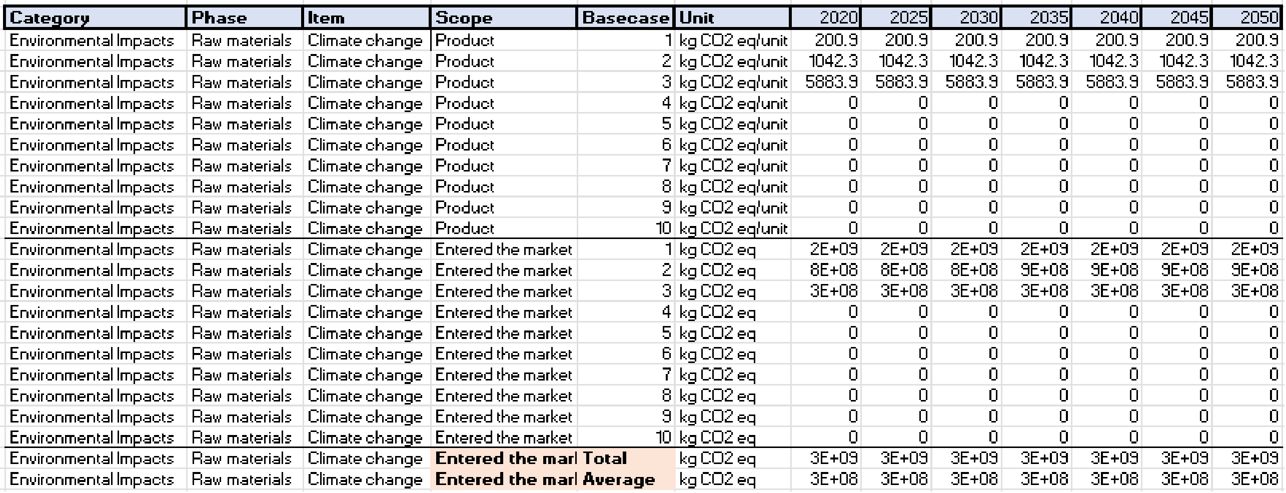
	sales (y – lifetime + 1)] / lifetime	[Impact (y) * (Sum of sales (y-1) to sales (y – lifetime + 1)/ lifetime
Maintenance and repair	Materials are considered to be "used" or "allocated" at the beginning of the product's lifetime for simplicity. Technically, maintenance should occur several times a year or less, and repair should occur once every several years, but exact information on this was not available. Stock calculation: Material per product (y) * Sales (y) = Material "used" (y)	Impacts are considered to "occur" or "allocated" at the beginning of the product's lifetime for simplicity. Technically, maintenance should occur several times a year or less, and repair should occur once every several years, but exact information on this was not available. Stock calculation: Impact per product (y) * Sales (y) = Environmental impact "entered the market (y)"
EOL	Results from the revised EcoReport tool do not provide output on material EOL, hence is not calculated for stock modelling.	Impacts "exit the market" after product's lifetime is up. Stock calculation for products with same lifetime throughout: Environmental impact "exit the market" (y) = Environmental impact (y – lifetime + 1)

Note: y = year.



Category	Phase	Item	Scope	Basecase	Unit	2020	2025	2030	2035	2040	2045	2050
Materials	Raw materials	Plastics	Product	1	g/unit	385	385	385	385	385	385	385
Materials	Raw materials	Plastics	Product	2	g/unit	1320	1320	1320	1320	1320	1320	1320
Materials	Raw materials	Plastics	Product	3	g/unit	6600	6600	6600	6600	6600	6600	6600
Materials	Raw materials	Plastics	Product	4	g/unit	0	0	0	0	0	0	0
Materials	Raw materials	Plastics	Product	5	g/unit	0	0	0	0	0	0	0
Materials	Raw materials	Plastics	Product	6	g/unit	0	0	0	0	0	0	0
Materials	Raw materials	Plastics	Product	7	g/unit	0	0	0	0	0	0	0
Materials	Raw materials	Plastics	Product	8	g/unit	0	0	0	0	0	0	0
Materials	Raw materials	Plastics	Product	9	g/unit	0	0	0	0	0	0	0
Materials	Raw materials	Plastics	Product	10	g/unit	0	0	0	0	0	0	0
Materials	Raw materials	Plastics	Impact quantity	1	kt	3.34	3.50	3.51	3.57	3.58	3.81	3.87
Materials	Raw materials	Plastics	Impact quantity	2	kt	1.00	1.07	1.04	1.09	1.16	1.13	1.18
Materials	Raw materials	Plastics	Impact quantity	3	kt	0.36	0.36	0.37	0.36	0.37	0.37	0.38
Materials	Raw materials	Plastics	Impact quantity	4	kt	0	0	0	0	0	0	0
Materials	Raw materials	Plastics	Impact quantity	5	kt	0	0	0	0	0	0	0
Materials	Raw materials	Plastics	Impact quantity	6	kt	0	0	0	0	0	0	0
Materials	Raw materials	Plastics	Impact quantity	7	kt	0	0	0	0	0	0	0
Materials	Raw materials	Plastics	Impact quantity	8	kt	0	0	0	0	0	0	0
Materials	Raw materials	Plastics	Impact quantity	9	kt	0	0	0	0	0	0	0
Materials	Raw materials	Plastics	Impact quantity	10	kt	0	0	0	0	0	0	0
Materials	Raw materials	Plastics	**Impact quantity**	**Total**	kt	4.70	4.93	4.92	5.02	5.10	5.31	5.43
Materials	Raw materials	Plastics	**Impact quantity**	**Average**	kt	0.47	0.49	0.49	0.50	0.51	0.53	0.54
Materials	Raw materials	Plastics	In use	1	kt	37.54	39.42	40.62	41.81	43.00	44.20	45.39
Materials	Raw materials	Plastics	In use	2	kt	14.11	14.80	15.23	15.67	16.10	16.54	16.98
Materials	Raw materials	Plastics	In use	3	kt	6.67	6.93	7.00	7.07	7.13	7.20	7.26
Materials	Raw materials	Plastics	In use	4	kt	0	0	0	0	0	0	0
Materials	Raw materials	Plastics	In use	5	kt	0	0	0	0	0	0	0
Materials	Raw materials	Plastics	In use	6	kt	0	0	0	0	0	0	0
Materials	Raw materials	Plastics	In use	7	kt	0	0	0	0	0	0	0
Materials	Raw materials	Plastics	In use	8	kt	0	0	0	0	0	0	0
Materials	Raw materials	Plastics	In use	9	kt	0	0	0	0	0	0	0
Materials	Raw materials	Plastics	In use	10	kt	0	0	0	0	0	0	0
Materials	Raw materials	Plastics	**In use**	**Total**	kt	58.32	61.15	62.85	64.54	66.24	67.94	69.63
Materials	Raw materials	Plastics	**In use**	**Average**	kt	5.83	6.12	6.28	6.45	6.62	6.79	6.96

Figure A 8: Example of stock output for materials in the raw materials phase



Category	Phase	Item	Scope	Basecase	Unit	2020	2025	2030	2035	2040	2045	2050
Environmental Impacts	Raw materials	Climate change	Product	1	kg CO2 eq/unit	200.9	200.9	200.9	200.9	200.9	200.9	200.9
Environmental Impacts	Raw materials	Climate change	Product	2	kg CO2 eq/unit	1042.3	1042.3	1042.3	1042.3	1042.3	1042.3	1042.3
Environmental Impacts	Raw materials	Climate change	Product	3	kg CO2 eq/unit	5883.9	5883.9	5883.9	5883.9	5883.9	5883.9	5883.9
Environmental Impacts	Raw materials	Climate change	Product	4	kg CO2 eq/unit	0	0	0	0	0	0	0
Environmental Impacts	Raw materials	Climate change	Product	5	kg CO2 eq/unit	0	0	0	0	0	0	0
Environmental Impacts	Raw materials	Climate change	Product	6	kg CO2 eq/unit	0	0	0	0	0	0	0
Environmental Impacts	Raw materials	Climate change	Product	7	kg CO2 eq/unit	0	0	0	0	0	0	0
Environmental Impacts	Raw materials	Climate change	Product	8	kg CO2 eq/unit	0	0	0	0	0	0	0
Environmental Impacts	Raw materials	Climate change	Product	9	kg CO2 eq/unit	0	0	0	0	0	0	0
Environmental Impacts	Raw materials	Climate change	Product	10	kg CO2 eq/unit	0	0	0	0	0	0	0
Environmental Impacts	Raw materials	Climate change	Entered the market	1	kg CO2 eq	2E+09	2E+09	2E+09	2E+09	2E+09	2E+09	2E+09
Environmental Impacts	Raw materials	Climate change	Entered the market	2	kg CO2 eq	8E+08	8E+08	8E+08	9E+08	9E+08	9E+08	9E+08
Environmental Impacts	Raw materials	Climate change	Entered the market	3	kg CO2 eq	3E+08	3E+08	3E+08	3E+08	3E+08	3E+08	3E+08
Environmental Impacts	Raw materials	Climate change	Entered the market	4	kg CO2 eq	0	0	0	0	0	0	0
Environmental Impacts	Raw materials	Climate change	Entered the market	5	kg CO2 eq	0	0	0	0	0	0	0
Environmental Impacts	Raw materials	Climate change	Entered the market	6	kg CO2 eq	0	0	0	0	0	0	0
Environmental Impacts	Raw materials	Climate change	Entered the market	7	kg CO2 eq	0	0	0	0	0	0	0
Environmental Impacts	Raw materials	Climate change	Entered the market	8	kg CO2 eq	0	0	0	0	0	0	0
Environmental Impacts	Raw materials	Climate change	Entered the market	9	kg CO2 eq	0	0	0	0	0	0	0
Environmental Impacts	Raw materials	Climate change	Entered the market	10	kg CO2 eq	0	0	0	0	0	0	0
Environmental Impacts	Raw materials	Climate change	**Entered the marl**	**Total**	kg CO2 eq	3E+09	3E+09	3E+09	3E+09	3E+09	3E+09	3E+09
Environmental Impacts	Raw materials	Climate change	**Entered the marl**	**Average**	kg CO2 eq	3E+08	3E+08	3E+08	3E+08	3E+08	3E+08	3E+08

Figure A 9: Example of stock output for environmental impacts in the raw materials phase