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Is repair of energy using products environmentally beneficial? The case of high voltage electric motors

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A R T I C L E I N F O

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A B S T R A C T

Repair is advocated as a circular strategy to improve the environmental performance of products. Whether this holds for very long-lived and energy intensive products has not been addressed. This study compares environmental impacts of two high voltage motors of different energy efficiency and assesses their use extension by repair with life cycle assessment (LCA). Due to high energy use, long lifetime and intensive use, the use phase dominates all environmental impacts, even resource depletion. Therefore, a higher energy efficiency is more beneficial than extending the use by repair, and if the energy efficiency is slightly reduced, the repair is not beneficial. Therefore, product requirements and users and manufacturers of such products should ensure designs with high energy efficiency rather than making the product repairable. Finally, the results highlight the importance of including resource use from electricity production and transmission in LCA of the use extension of energy using products.

1. Introduction

For improving energy and resource efficiency of products as well as achieving carbon neutrality, the new circular economy (CE) action plan from the European Commission announced an update of the Ecodesign directive (European Commission, 2009) with requirements for making products more durable, reusable and repairable (European Commission, 2020). These strategies for use extension are part of the CE strategies suggested for improving a product's environmental performance (Böckin et al., 2020). However, trade-offs between life cycle phases or impact categories may occur (Böckin et al., 2020; Keoleian, 2013).

For products requiring direct electricity input during use, referred to as energy using products (EuP) by the original Ecodesign directive (European Commission, 2005), life cycle assessments (LCA) have identified trade-offs between efficiency improvement and use extension (such as reuse, maintenance, repair or remanufacture) (Böckin et al., 2020; Boldoczki et al., 2020; Glöser-Chahoud et al., 2021; Hummen and Desing, 2021). Specifically, extending product use is not necessarily beneficial if efficiency decreases with wear and tear or if more efficient technology has become available (Bakker et al., 2014; Hummen and Desing, 2021; Keoleian, 2013). From studies on the effects of use extension on the environmental performance of EuP, several influencing parameters were identified (Jerome, 2022) including the speed of energy efficiency evolution by technology development (Ardente et al., 2018; Ardente and Mathieux, 2014; Bakker et al., 2014; Baxter, 2019; Hummen and Wege, 2021; Keoleian, 2013; Schischke et al., 2003), the environmental impact category considered (Ardente and Mathieux, 2014; Bobba et al., 2016), the intensity of use (Boldoczki et al., 2020; Keoleian, 2013; Pérez-Belis et al., 2017; Zink et al., 2014) or the share of the use phase in the life cycle impact of a product (Boldoczki et al., 2020; Keoleian, 2013). Those parameters differ with the product and geographical and temporal scope. For instance, Glöser-Chahoud et al. (2021) concludes that increasing the technical lifetime of refrigerators is becoming more relevant with the slower development of efficiency and the development of cleaner electricity mixes. Additionally, studies on the environmental benefits of repair, reuse and remanufacturing of EuP conclude that benefits depend on the impact of the use extension process (Ardente et al., 2018; Ardente and Mathieux, 2014; Biswas et al., 2013; Bovea et al., 2020; Pini et al., 2019; Proske et al., 2020) and the duration of additional use provided (Ardente and Mathieux, 2014; Baxter, 2019; Biswas et al., 2013; Bobba et al., 2016; Ljunggren Söderman and André, 2019; Tecchio et al., 2016).

However, the literature on environmental assessments of use extension of EuP is limited in two respects. First, little attention is given to resource depletion impacts, especially related to mineral resources that are among the main constituents of EuP. Some studies assess

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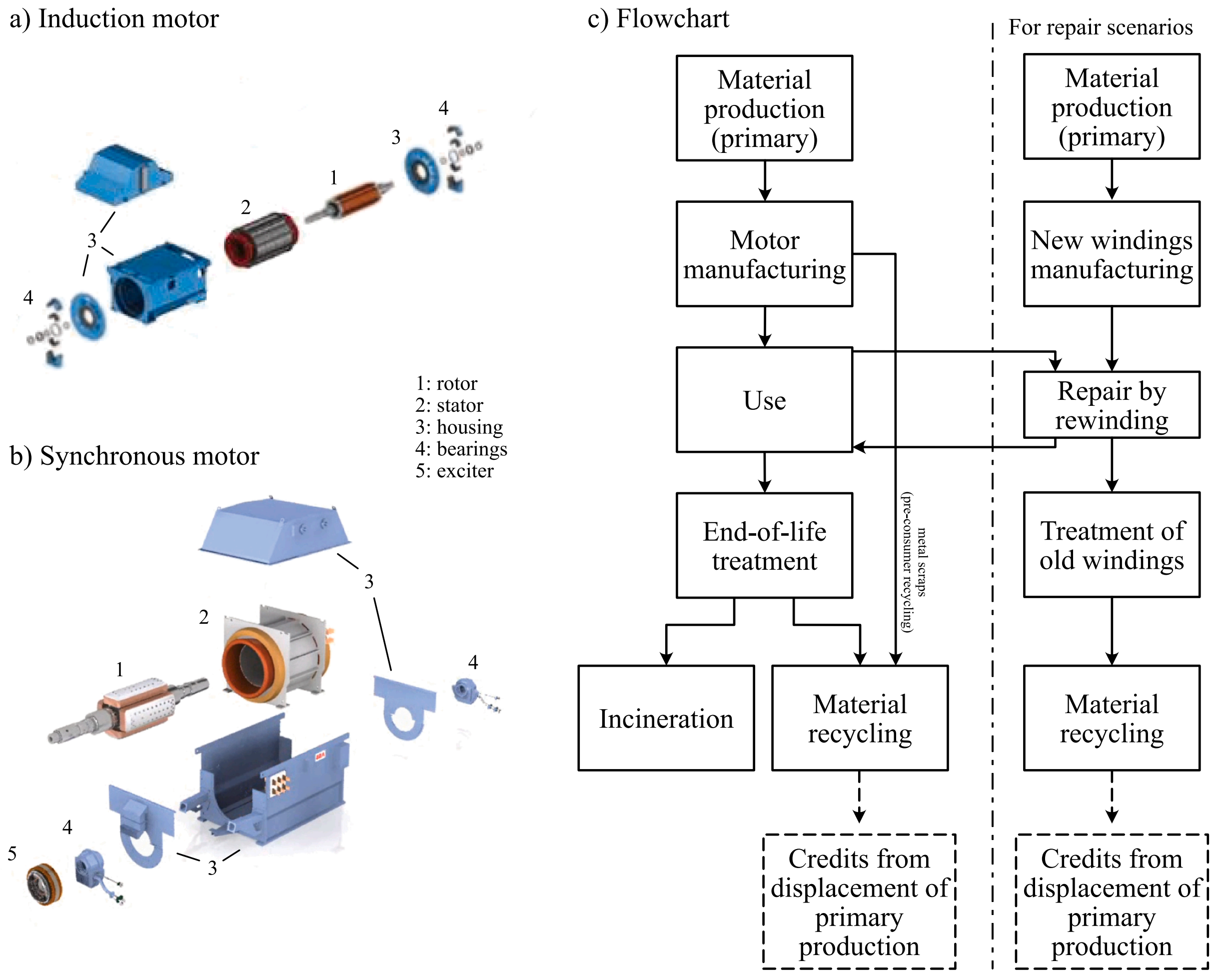

Fig. 1. Exploded view of the products under study: a) an IM and b) SM, and c) a simplified flowchart of the system.

resource depletion among other midpoint indicators and limit the conclusions to that production is specifically dominant for this impact category (Cheung et al., 2018; Güvendik, 2014; Schau et al., 2012). Few studies provide more conclusions for use extension: greater benefit is achieved due to the production being dominant (Bobba et al., 2016; Chen and Lu, 2017; Iraldo et al., 2017), energy efficiency evolution by technological development influences less this benefit compared to other impact categories (Ardente et al., 2018; Tecchio et al., 2016) but the extent of the repair affects more the results for resource depletion than for other impacts (Ardente and Mathieux, 2014). Thus, there is little discussion on the effects of use extension on mineral resource depletion, although resource efficiency is seen as one of the most important drivers for implementing CE strategies. Second, these studies focus on small- and medium-sized EuP (Jerome, 2022) such as household appliances (Ardente and Mathieux, 2014; Bobba et al., 2016; Boustani et al., 2010), smartphones (Güvendik, 2014; Proske et al., 2020; Zink et al., 2014), laptops (André et al., 2019) or car engines (Smith and Keoleian, 2008), leaving out more long-lived and energy intensive (i.e., with a high energy use and operating time) products.

An example of such an energy intensive product is high voltage (HV) electric motors. Such big and stationary electric motors are typically used for at least 20 years and deliver output powers ranging from 1 to 60 MW, with considerably higher annual energy use and operating time than smaller EuP (see Figs. A.1 and A.2 in Appendix A). Electric motors use 50% of the electricity in Europe (Auer and Meincke, 2018) and motors with outputs above 500 kW represent 15% of the European industrial electricity consumption (de Almeida et al., 2003). Two main designs of HV motors exist: induction motors (IM) and synchronous motors (SM), where the latter are more energy efficient but require more copper. HV motors are often used until failure which often occurs in the stator windings for motors with an output above 2 MW (Thorsen and Dalva, 1999). These windings, made of copper, could be replaced through rewinding (Cao and Bradley, 2005). Reuse and remanufacturing for use by new customers are rare since these big motors are customized to the specific use and thus unfit for other uses.

This article aims to study the potential environmental impacts of improved energy efficiency and extended use through repair for long-lived and energy intensive products. Consequences on environmental performance and specifically resource efficiency of use extension for this product category are explored by comparing LCA results for the two designs of HV motors and their repair. Thus, the study can enrich the discussion on consequences of use extension of EuP, extending the range of products studied beyond small- and medium-sized electrical and electronic equipment (EEE) products and vehicles. This is relevant both in policymaking for different types of products, and for actors involved in the life cycle of those products, e.g., manufacturers or users, when prioritising their actions for improving products' environmental performance.

2. Method

2.1. Case description

HV motors are stationary motors used for example for actioning of pumps, compressors, or fans in production in, e.g., oil and gas, chemical and metal industries. This study addresses motors used in the air separation industry with an output power of 16 MW. They are used intensively: except for two weeks of annual maintenance, they run at full load 24 h a day.

The two motor designs, IM and SM, are studied. The energy efficiency is 97.3% for the IM and 98.3% for the SM. Both motor designs are made of: 1) a rotor, the rotating component, 2) a stator, the static component, 3) a housing and cooler, and 4) bearings (Figs. 1a and b). These components are similar for both designs except for the rotor. Additionally, an exciter, similar to a small IM, is required for the SM. The stator and rotor are made of insulated copper windings fixed on steel and electrical steel structures. The electricity flowing in the windings generates magnetic fields used to generate a rotating movement. The housing and cooler are made of steel.

2.2. Goal and scope

To study the effects of use extension of EuP on environmental performance and resource efficiency, the LCA compares (1) the two designs of HV motors and (2) each HV motor with extended use through repair of stator windings to motors without repair. Cradle-to-gate attributional LCAs are performed with a functional unit of one year of motor use to provide 16 MW over 50 weeks full-time for four different alternatives: 1) the IM used for 20 years, 2) the SM used for 20 years, 3) the IM repaired after 20 years and 4) the SM repaired after 20 years. Little information is available about the average lifetime of a repaired motor, so the additional years of use after repair is a variable parameter. Several scenarios are assessed for alternatives 3) and 4):

- (+1), (+10) and (+20): scenarios without efficiency reduction and one, 10 or 20 years of use extension respectively,
- (+1↓), (+10↓) and (+20↓): scenarios with an efficiency reduction and one, 10 or 20 years of use extension respectively.

In all alternatives, the motors are sent to material recycling at end-of-life with some residual non-recyclable fractions incinerated.

Data for the production and use of HV motors were collected from the manufacturer and the literature. Additionally, a user provided knowledge on the use profile, maintenance and end-of-life treatment, and information on the treatment of HV motors was collected from a recycling facility. Background data were modelled with average data from ecoinvent 3.8 cut-off (Wernet et al., 2016). Modelling and calculations were done using Activity Browser and brightway (Mutel, 2017; Steubing et al., 2020). Motor manufacturing and end-of-life pre-treatment are located in Sweden and are assumed to be representative of European conditions. Raw material production, recycling and incineration are based on European markets, or global markets if the former is not available in ecoinvent. The motors are used in Sweden but, with a sensitivity analysis, other electricity productions are explored. The Swedish electricity mix is a low-carbon production with a high share of nuclear (40%) and hydroelectricity (38%) production (see Table S.7 in the supplementary information (SI)). A very low-carbon mix is represented by hydroelectricity production, while a carbon-intensive non-renewable electricity mix is represented by oil-based electricity production only.

Unlike a strictly attributional approach, the avoided burden approach was used for pre- and post-consumer recycling allocation. As recycling is one of the post-use CE strategies (Böckin et al., 2020), the recycling of the motors is important to model. To avoid double counting of recycling, the material production for motor manufacturing is done with datasets representing only primary production based on an adjustment of ecoinvent datasets described in Chordia et al. (2021), while recycled materials are accounted as displacing primary production (Fig. 1c). Incineration with energy recovery and other material recycling than metal scraps from the motor manufacturing and motors' end-of-life treatment were modelled with the cut-off allocation approach.

Table 1
Material composition of the studied IM and the SM after scaling to an output power of 16 MW.

Material	Induction motor (IM) (ton)	Synchronous motor (SM) (ton)
Steel, unalloyed	12.3	9.0
Steel, low-alloyed	4.1	9.2
Electrical steel	14.3	9.0
Copper, unalloyed	2.7	3.8
Copper, alloyed	0.9	0
Insulation	0.4	0.3
Total	34.7	31.3

The most recent recommendations for a broad range of midpoint impact categories, and thus the recommended categories by the environmental footprint method (EF3.0) (Zampori and Pant, 2019) are assessed except mineral resource depletion impact categories. Instead, the crustal scarcity indicator (CSI) (Arvidsson et al., 2020b, 2020a) is used since it better reflects impacts on potential long-term scarcity (André and Ljunggren, 2022; Arvidsson et al., 2020b). The CSI is based on average crustal concentrations and, in contrast to other depletion methods, free from temporally variable factors such as extraction rates, reserves and prices unsuitable for assessing long-term depletion.

3. Data collection and modelling

The system modelled is presented in this section, while more information is available in the SI.

3.1. Motor composition

The material composition of the motors is based on specific motors, provided by the manufacturing company as representative motors for HV IM and SM (Table 1). The motors have similar characteristics: running in a non-hazardous environment, output power, application, and cooling system. Since the SM has a slightly lower output power (15.9 MW), a linear approximation is performed, and 1.006 SM are estimated to provide the same output as the IM (16 MW).

3.2. Manufacturing

Manufacturing is similar for the two motor designs. Electrical steel sheets are punched, stacked and welded to form the stator core in which insulated copper windings are inserted. The component is then insulated with vacuum-pressed resin. The rotor of the IM is made of punched electrical steel sheets, copper windings and a machined steel shaft. The rotor of the SM is manufactured by inserting coils on a machined steel shaft and does not require electrical steel. The housing frame, cooler and bearings are added during the assembly phase. Each HV motor is then painted and tested.

The manufacturing, especially the punching of electrical steel, generates metal scraps that are sent to recycling. The quantity of scrap is estimated based on the difference between the ordered material quantity and the remaining quantity in the final product. Electricity consumption for the testing of HV motors and the vacuum pressing process, the two most energy-intensive processes in production, is estimated with data from the company. Otherwise, data on low voltage (LV) IM production from Nordelöf et al. (2017) are used since the manufacturing of LV IM is similar to that of HV motors.

3.3. Use

Energy consumption in the use phase consists of useful energy to be delivered by the motor, and of energy losses reflected by the energy-efficiency value of the motor. As the purpose of this study is to compare motors delivering the same output and the production system fed by those motors is outside the scope, only the electricity due to

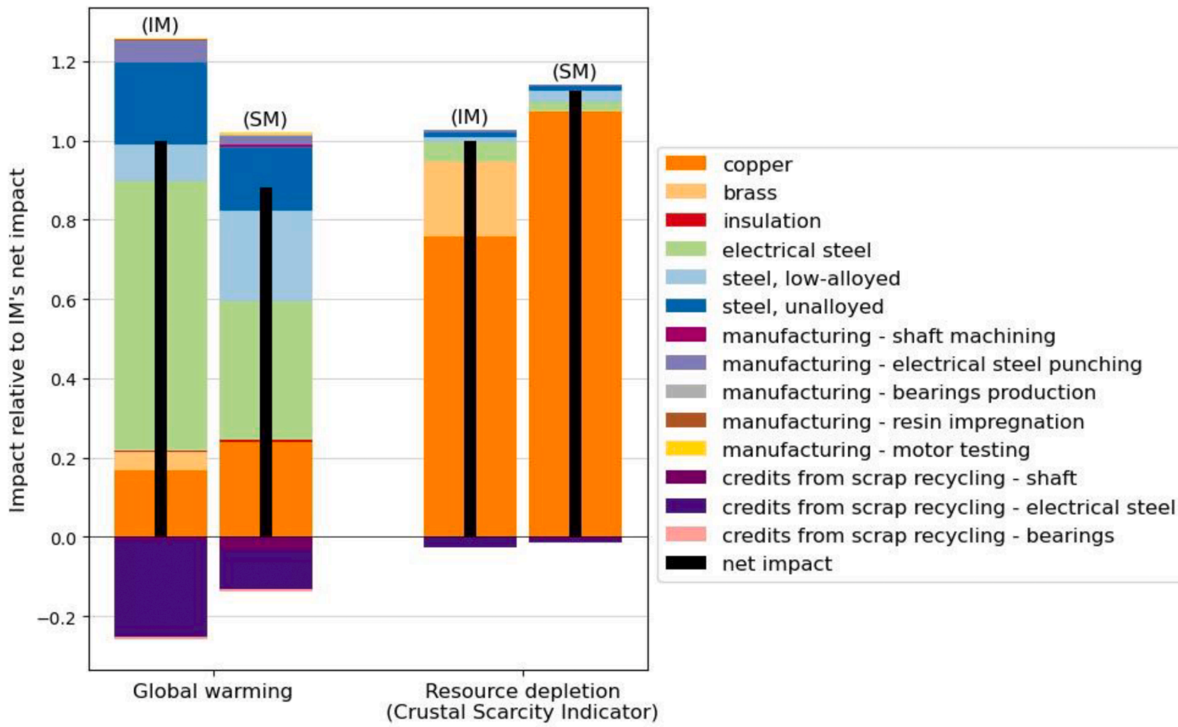

Fig. 2. Cradle-to-gate LCA results for the IM and the SM relative to IM's net impact.

energy losses is included. The energy efficiency can be estimated to remain constant during operation according to the manufacturer. Proper maintenance is assumed, involving the regular replacement of some small components such as filters, bolts and bearings. As the weight of those exchanged components is not significant in the bill of materials, additional component production related to maintenance is excluded. Transportation from the manufacturer and to the recycling facility is not included. It was identified as representing a negligible share of the environmental impact of HV motors (Westberg, 2021) and, in addition, the comparison of the motors does not include variations in geographical location for use.

3.4. *End-of-life management*

HV motors are sent to recycling at end of life. The motors are first dismantled and then shredded in hammer mills. After shredding and sorting, insulation is incinerated, and copper and steel are sent to their respective recycling processes. Separation rates are estimated from Tillman et al. (2020), with the difference that the size of HV motors leads to the copper being more easily separated from steel components. Ecoinvent datasets are used to model incineration and recycling.

3.5. *Repair by rewinding*

Stator rewinding is performed by pulling out and recycling the old copper windings, and by producing new windings that are inserted into the existing stator core. The energy efficiency of the repaired motor may be affected, especially if higher repair quality is not achieved, e.g., if the winding configuration is modified (Cao and Bradley, 2005). With a repair of good quality, energy efficiency is decreased by 0.1% on average and up to 0.7% (Cao and Bradley, 2005; EASA and AEMT, 2021). Without control of repair quality, reductions reported are 0.6% on average and up to 1% (Cao and Bradley, 2005) to 2% (Penrose and Bauer, 1995). Therefore, an efficiency reduction of 0.6% is chosen for repair scenarios (+1↓), (+10↓) and (+20↓).

4. Results and discussion

Cradle-to-grave results for all impact categories lead to the same conclusions for the comparison of the motor designs and for their repair. For cradle-to-gate results, two groups of impact categories can be distinguished, depending on whether the contribution from steel dominates. This section focuses on the following impact categories (for other results, see the SI):

- global warming (GW) as a category dominated by the contribution of steel in cradle-to-gate results. This category is chosen as often in focus in governmental and companies' environmental goals,
- mineral resource depletion with the crustal scarcity indicator (CSI) as a category dominated by the contribution of copper in cradle-to-gate results. Besides, resources are in focus in the overarching aims of CE and HV motors are mainly made of materials from mineral raw materials.

4.1. *Comparison of the motor designs*

The difference in material content leads to different cradle-to-gate (i.e., motor production including material production, motor manufacturing and pre-consumer recycling of metal scraps during manufacturing) results of the two motor designs (Fig. 2). Compared to the IM, the SM results in lower GW as it has a lower electrical steel content. The high impact of electrical steel is due to two aspects: 1) the punching of electrical steel generates a lot of scraps and 2) steel production is performed with fossil energy sources and releases carbon dioxide. However, the SM results in a higher resource depletion impact as it has a higher copper content. In contrast to steel production which does not require elements with high crustal depletion potential, copper is co-mined with tellurium, molybdenum, selenium, silver, gold and rhenium which all have a significant crustal depletion potential (Arvidsson et al., 2020b).

In the cradle-to-grave results, where the use and end-of-life phases

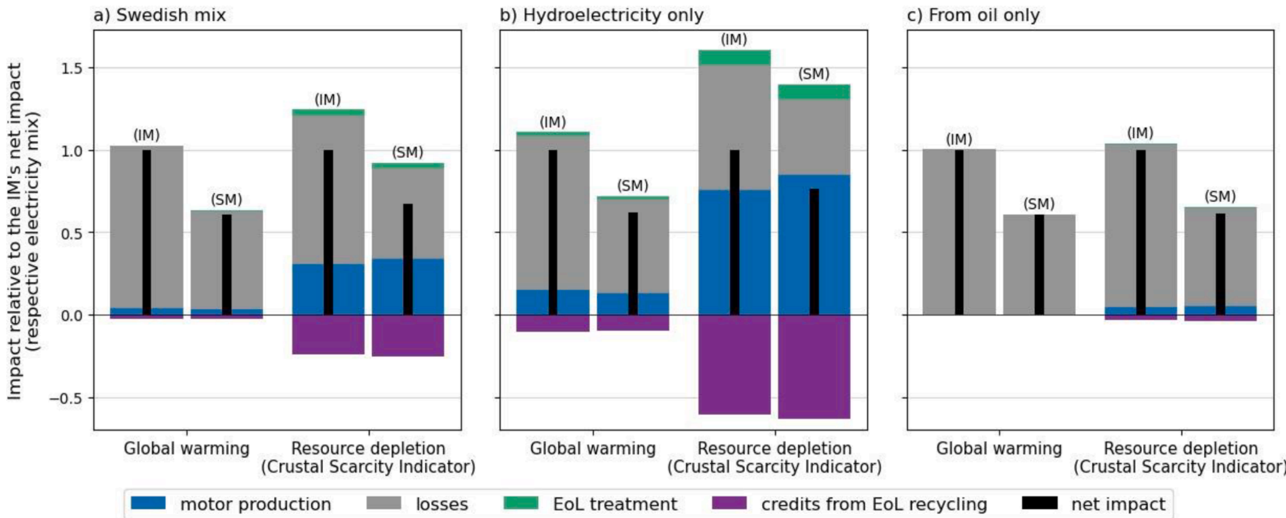

Fig. 3. Comparison of the cradle-to-grave LCA results for the IM and SM with different electricity production for motor use: a) Swedish electricity mix, b) from hydroelectricity only and c) from oil-based power only.

are added to motor production, the SM results in a lower impact than the IM for both impact categories (Fig. 3). Energy losses during use dominate the life cycle impact. Therefore, the better energy efficiency of the SM results in a significant impact reduction. For resource depletion, this reduction is high enough to outweigh the higher cradle-to-gate impact for the SM. Changing the electricity mix from very carbon-intensive to very low-carbon does not change this conclusion but reduces the relative difference between IM and SM by a factor of 1.04 for GW and 1.64 for resource depletion. Due to the dominance of losses, the cradle-to-grave impact of a motor is also largely influenced by the electricity mix. For the IM, the impact decreases by a factor of 4 and increases by a factor of 19 for global warming with hydroelectricity and oil-based production respectively and decreases by a factor of 2,5 and increases by a factor of 6.8 for resource depletion. The credits from end-of-life recycling are lower than the impact of motor production due to the impact from energy use in manufacturing and lower quantities of material leaving the recycling process than entering the motor production.

4.2. Use extension by repair

The results per year of use for the different scenarios with repair and the results from the sensitivity analysis are presented in Fig. 4. Conclusions for the IM (Figs. 4a, c and e) and the SM (Figs. 4b, d and f) are similar. The rewinding (i.e., the sum of the impact from the recycling of old windings, credits from winding recycling and production of new copper windings) has a lower impact than producing and recycling a new motor due to the lower material requirement. The evolution of the net impact of HV motors with repair without efficiency reduction is very little for GW, but more apparent for resource depletion (Fig. 4). The repair does not lead to a reduction of net impact per functional unit with only a short additional use. The minimum additional lifetime for the repair to be beneficial *(L_{add})* is:

$$L_{add} = \frac{I_{repair}.L_i}{I_{prod}} \tag{1}$$

with I_{repair} the sum of the impact from rewinding, old winding recycling and credits from old winding recycling, L_i the initial lifetime of the motor and I_{prod} the sum of the impact from motor production, recycling and credits from recycling (detailed justification in section S.4 in the SI).

For GW, the additional lifetime should be no less than one-tenth of the initial lifetime for both designs, and for CSI, half of the initial lifetime for the IM and one-third for the SM, and so for all types of electricity production in the use phase. This is visible in Fig. 4, especially for resource depletion and cleaner electricity mixes: repair scenarios (+1) do not result in impact reduction compared to (M), but (+10) and (+20) do. As energy losses, and not motor production with credits from recycling, dominate the impact, repair leads to a smaller impact reduction than the impact reduction from selecting the more efficient SM over the IM shown in Fig. 3.

With an efficiency reduction of 0.6% after repair, repair scenarios for all tested additional lifetimes (+1↓, +10↓ and +20↓ in Fig. 4) result in higher net impact than the motor without extended use (M). The higher losses during the extended use offset the gain from the lower material requirements for all electricity mixes. Changing the electricity mix from very carbon-intensive (Figs. 4e and f) to very low-carbon (Figs. 4c and d) increases the relative difference between repaired motors and new motors.

When efficiency reduction after repair is changed, Fig. 5 shows that the impact from additional losses generated by this efficiency reduction leads to an increase of the required additional lifetime for motor repair to result in a lower impact per year of use than a new motor. If the efficiency reduction is too high, the impact per year of use of the repaired motor never reaches a value below a new motor, even after an infinite extended use after repair. The maximum energy efficiency reduction allowed after repair for an impact reduction to be possible ($\eta_{\Delta,max}$) is:

$$\eta_{\Delta,max} = \eta \frac{I_{prod}}{I_{prod} + \frac{I_{el}.E_{out}.L_i}{\eta}} \tag{2}$$

with I_{el} the impact from the production of 1 kWh of electricity, E_{out} the annual energy output calculated as the power output times the number of hours of use per year, and η the energy efficiency of the motor before repair (detailed justification in sections S.4 in the SI).

This threshold could be increased by a cleaner electricity mix, a higher energy efficiency, or, for a motor with a given design, a shorter initial lifetime and lower energy output. In this case, with an initial use of 20 years, the maximum efficiency reduction is 0.04–0.05% for GW and 0.3–0.4% for CSI for the two motor designs studied and electricity production from the Swedish electricity mix (Fig. 5). But with oil-based electricity only, a reduction of only 0.002% for GW and 0.05% for resource depletion is sufficient for the repair not to be beneficial, and 0.2% and 1% respectively in the case of hydroelectricity only.

A small efficiency reduction quickly leads to the repair to be not beneficial over a new motor or to an increase of the required additional lifetime for the repair to be beneficial. It is therefore especially important for highly energy consuming products that repair maintains a high

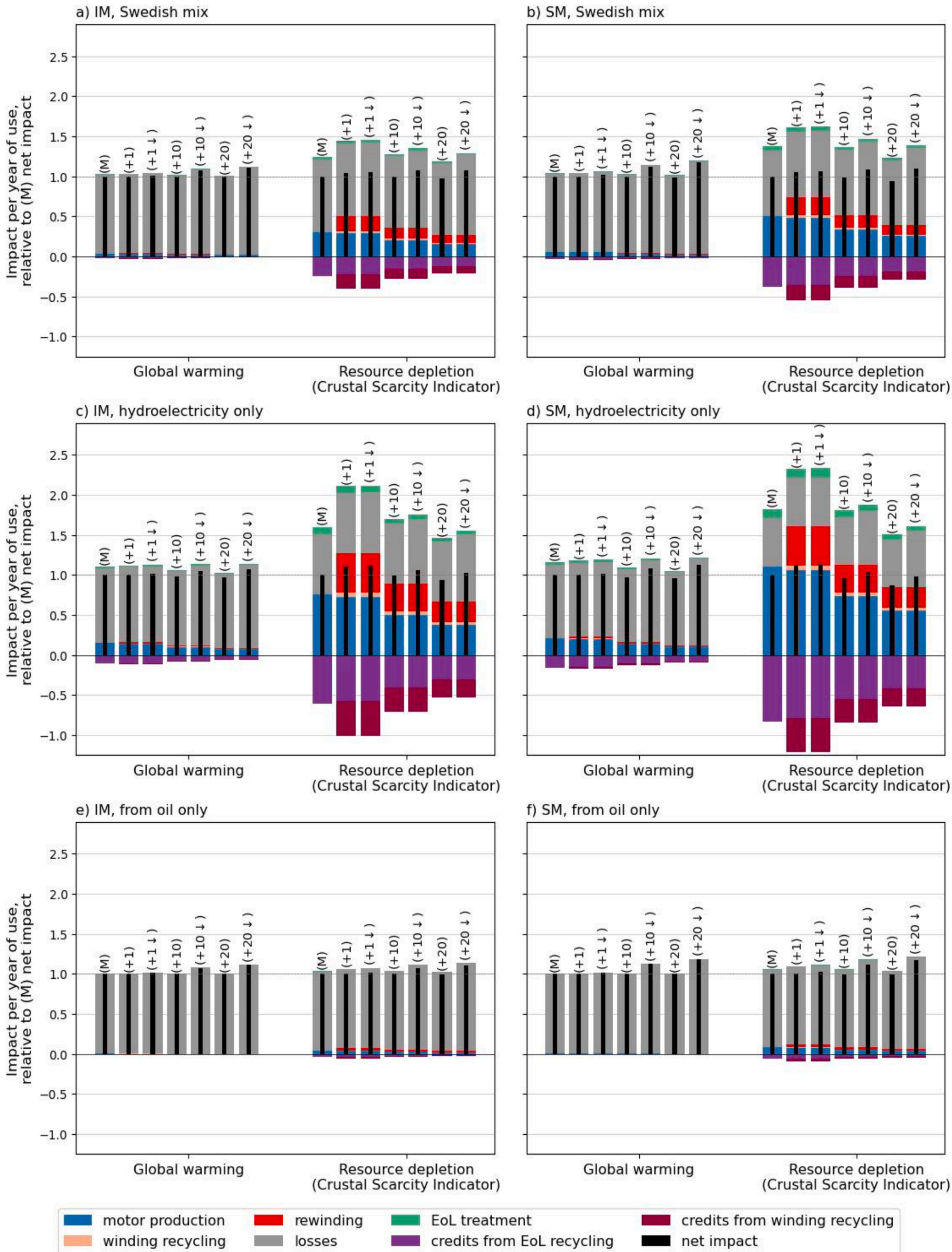

Fig. 4. Cradle-to-grave LCA results per year for the motor used for 20 years (M), and for the motor with different scenarios for repair for: a), c) and e) the IM using electricity from the Swedish mix, hydroelectricity production only and from oil only respectively, and b), d) and f) the SM using electricity from the Swedish mix, hydroelectricity production only and from oil only respectively. Repair scenarios with a one-, 10- or 20-year use extension respectively are noted (+1), (+10), and (+20) when without efficiency reduction and (+1↓), (+10↓), and (+20↓) when with an efficiency reduction of 0.6%.

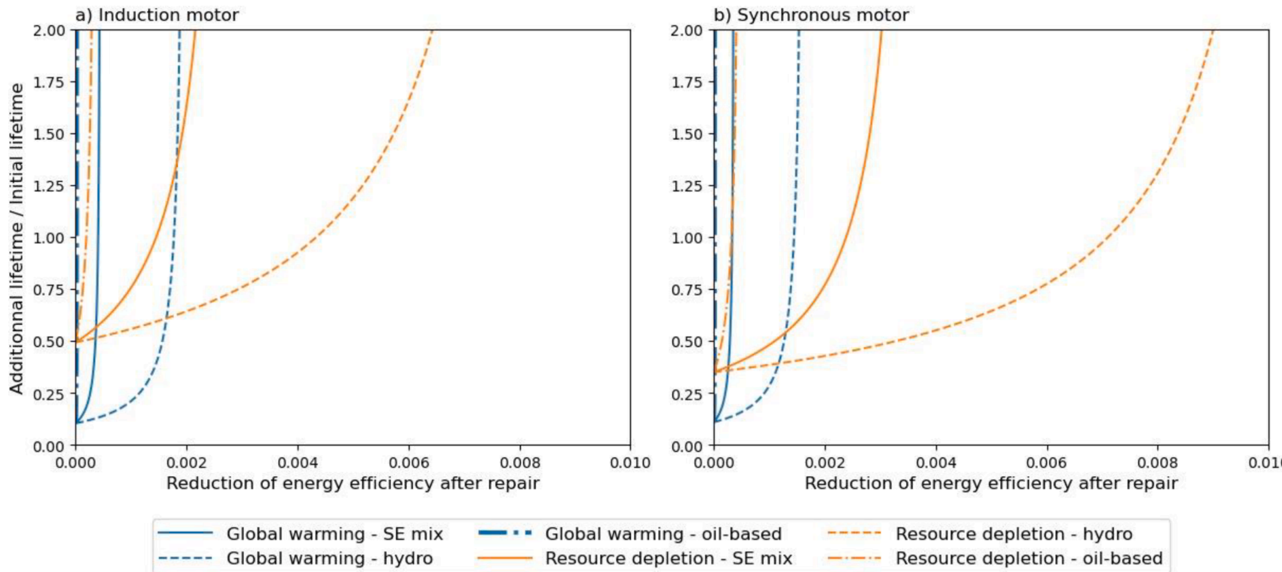

Fig. 5. Minimum additional lifetime, expressed as a fraction of the initial lifetime, for the repair to result in lower impact per year of use than the motor without repair as a function of efficiency reduction after repair for a) the IM and b) the SM.

energy efficiency.

4.3. Dominance of the impact from electricity production

For both impact categories, electricity production for the losses during HV motor use dominates the cradle-to-grave life cycle impact. Although the dominance of the use phase in LCA results is common in the literature for EuP (e.g., in the impact of washing machines in terms of eco-indicator 99 (Devoldere et al., 2009), in the cumulative energy demand of refrigerators (Boustani et al., 2010), in GW and primary energy demand of video projectors (Cheung et al., 2018), or in GW of smartphones (Güvendik, 2014), CML impact categories for LV IM (Cassoret et al., 2019)), it is rarely the case for resource depletion (Ardente et al., 2018; Ardente and Mathieux, 2014; Bobba et al., 2016).

For HV motors, resources used in energy production and transmission (background production system) are more important than the ones used in the motors themselves (foreground production system) for resource depletion impacts for all three electricity mixes. Oil dominates the impact of oil-based electricity production (Fig. B.1 in Appendix B). For the Swedish electricity mix, the impact from losses originates from nuclear and fossil electricity production (uranium and coal) and copper mining for transmission network production (tellurium, copper, molybdenum, selenium, and rhenium). For hydroelectricity production, coal for cement production used in facilities construction is significant. For all three mixes, resource use for transmission infrastructures (tellurium, copper, molybdenum, selenium, and rhenium from copper mining) gives rise to a notable resource depletion impact (Fig. B.1 in Appendix B). In the datasets from ecoinvent used for the modelling of electricity production in all European countries, the quantity of transmission lines allocated to the production and delivery of electricity is based on data for Switzerland from 2010 (Itten et al., 2014). For Sweden, a country less densely populated than Switzerland, this quantity might be higher. Besides, this quantity may have increased with time due to the development of renewable energy productions, Jorge and Hertwich (2014) estimating an increase of 10% between 2014 and 2020. Thus, more attention should be given to the transmission networks accounting for the specific geographical location, as this choice is significant for the resource depletion impact.

These results show that considering the resources in the system for energy production and transmission is important to take into consideration when studying CE strategies, especially for products with significant energy use such as EuP.

4.4. High energy efficiency is key

Choosing and maintaining high energy efficiency is key to reducing HV motors' environmental impact. The benefit from use extension by repair is small and uncertain compared to replacement with more efficient technology. This is especially the case in countries with a high share of fossil electricity production as a small (>0.05%) efficiency reduction after rewinding is sufficient for the repair not to be beneficial.

For LV motors, Kiatkittipong et al. (2008) points to similar conclusions: replacement with a more efficient technology is more beneficial in terms of resource use impact expressed as cumulative energy consumption than repair. The importance of the use phase in life cycle results seems to be the determining factor for use extension of a EuP to be beneficial. By studying a range of EEE, Boldoczki et al. (2020) states that use extension by reuse leads to significant savings when the use phase is less dominant than the production, but not for inefficient devices with a dominating use phase for most impact categories. However, Boldoczki et al. (2020) finds that reuse still represents a high saving potential for mineral resource depletion. In the case of HV motors, due to their very intensive use, high energy requirement and long lifetime, losses are dominant even for mineral resource depletion, leading to resources that are not in the product contributing more than resources in the product. Use extension does not lead to a significant impact reduction potential, not even for resource depletion and with very clean electricity mixes.

4.5. CE strategies for HV motors

This study focuses on repair and improved energy efficiency of HV motors by design. Other alternatives for use extension are reuse, increasing technical lifetime by design, maintenance and remanufacturing (Böckin et al., 2020). In this study, maintenance is assumed to be performed as recommended by the manufacturer resulting in a product of good quality as long as possible. As for the evolution of energy efficiency, no radical increase in the technical lifetime by design appears to be expected. Reuse and remanufacturing are sometimes performed on LV motors but maintaining high efficiency and other required performance is a challenge (Tiwari et al., 2021). The process is still costly and uncertain due to the variability of designs and the state of a motor after operation. For HV motors, their high customization and

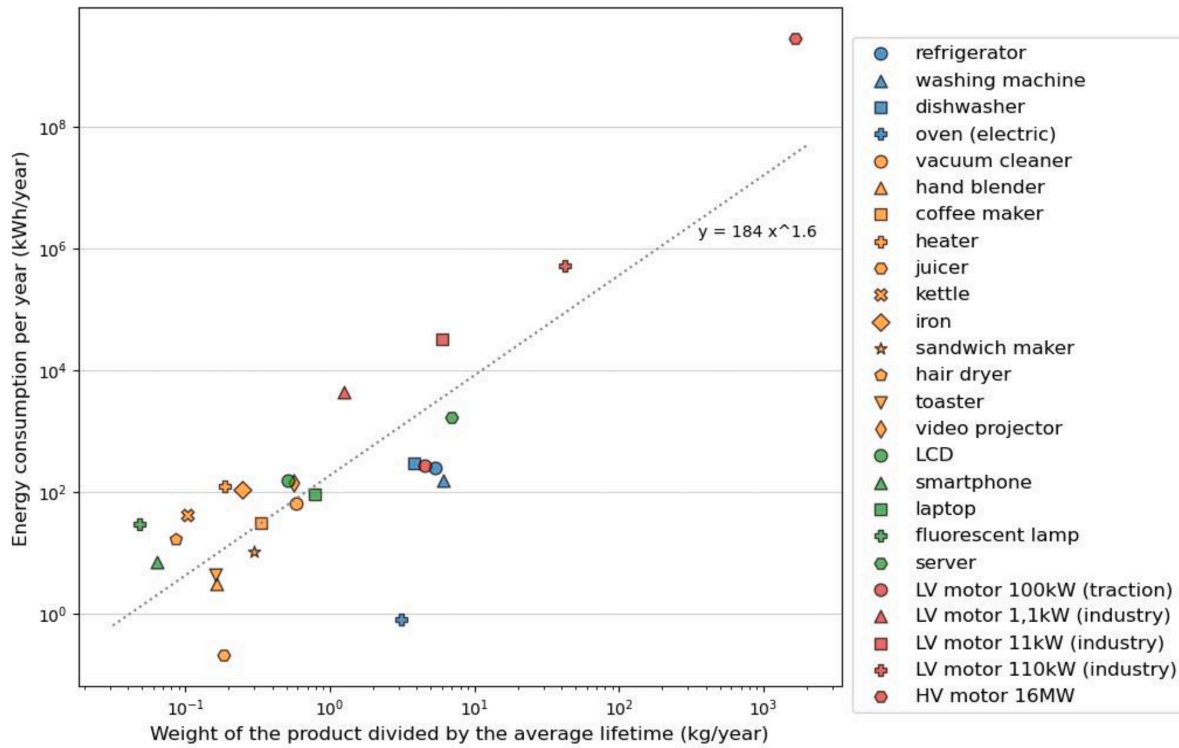

Fig. A.1. Comparison of the weight divided by the average lifetime and annual energy consumption of different EuP (logarithm scale). Data are from Baxter (2019) (refrigerator), Tecchio et al. (2016) (washing machine, dishwasher), Iraldo et al. (2017) (electric oven), Bovea et al. (2020) (vacuum cleaner, hand blender, coffee maker, heater, juicer, kettle, iron, sandwich maker, hair dryer, toaster), Cheung et al. (2018) (video projector), Pini et al. (2019) (liquid crystal display (LCD), laptop, fluorescent lamp), Proske et al. (2020) (smartphone), Ardente et al. (2018) (server), Nordelöf et al. (2019) (LV traction motor), and de Almeida et al. (2014, 2003) (stationary LV motors).

limited number in the industry hinder the possibility for one specific motor to be suitable for another use. HV motors are expected to fit the production, and not the production to fit a standardized motor selection. Customization is for example linked to the electricity network performance or configuration (e.g., hazardous environment) of the operating place. Besides, the responsibility for degraded performance after reuse/remanufacturing is unclear, which limits even further the possibility for use extension of a motor or a component. Therefore, remanufacturing and reuse of HV motors are very seldom performed.

4.6. Implications for actors

This study points to the importance of energy efficiency standards. For electric motors, some already exist on minimum efficiency of new LV motors. Extending efficiency requirements to HV and repaired motors is essential from an environmental point of view and, for energy intensive EuP, would lead to higher benefits than use extension. Requirements to ensure a long technical lifetime to avoid the risk of performance degradation during repair could also be possible as the evolution of energy efficiency with technological development for HV motors has been slow for the last 10–15 years and no radically different technology breakthrough appears to be expected.

Targeting use extension for incoming Ecodesign directives in the framework of the CE action plan has been pointed out as increasingly relevant for EuP due to the impact reduction from the use phase with continuous energy efficiency improvement and due to a shift to cleaner energy production (Bakker et al., 2014; Glöser-Chahoud et al., 2021). However, this study points to that such targets should be complemented by requirements to ensure high quality of repair to maintain the efficiency of EuP for use extension to have a positive environmental impact. For LV motors, uncareful repairs and remanufacturing have been pointed out as leading to significant additional energy consumption at a national level by Vieira et al. (2021).

For users of HV motors, relevant actions from an environmental point of view would be to prioritise SM and the most efficient motor designs when building a new production or exchanging an existing motor, and to maintain the original energy efficiency through effective maintenance and repair of good quality when a repair is needed. HV motor manufacturers can support these actions by ensuring motors of durable quality and facilitating high-quality repair by design.

Finally, the dominance of the impact from electricity production and transmission during the use of energy intensive EuP shows that implementing strategies for reducing the resource depletion impact from the electricity system be of higher priority than on the products themselves to increase resource efficiency.

5. Conclusion

This study looks at the life cycle environmental and resource depletion impact of use extension and improved efficiency by design of a long-lived and energy intensive product through the case of HV motors.

The energy losses during the use phase dominate the life cycle impact, both for GW and mineral resource depletion, due to the long lifetime, high energy output and intensive use of HV motors. Therefore, improving energy efficiency leads to more significant life-cycle environmental impact reductions than extending the use by repair. Unlike EuP with shorter and less intensive use, the potential benefit from reuse is also low for resource depletion impact and when very low carbon electricity mixes are used.

The environmental performance of energy intensive HV motors is also highly sensitive to energy efficiency reduction when performing repair, especially in the case of a carbon-intensive electricity mix. A small energy efficiency reduction leads to the repair not being beneficial. Measures to guarantee a high quality of repaired EuP with an

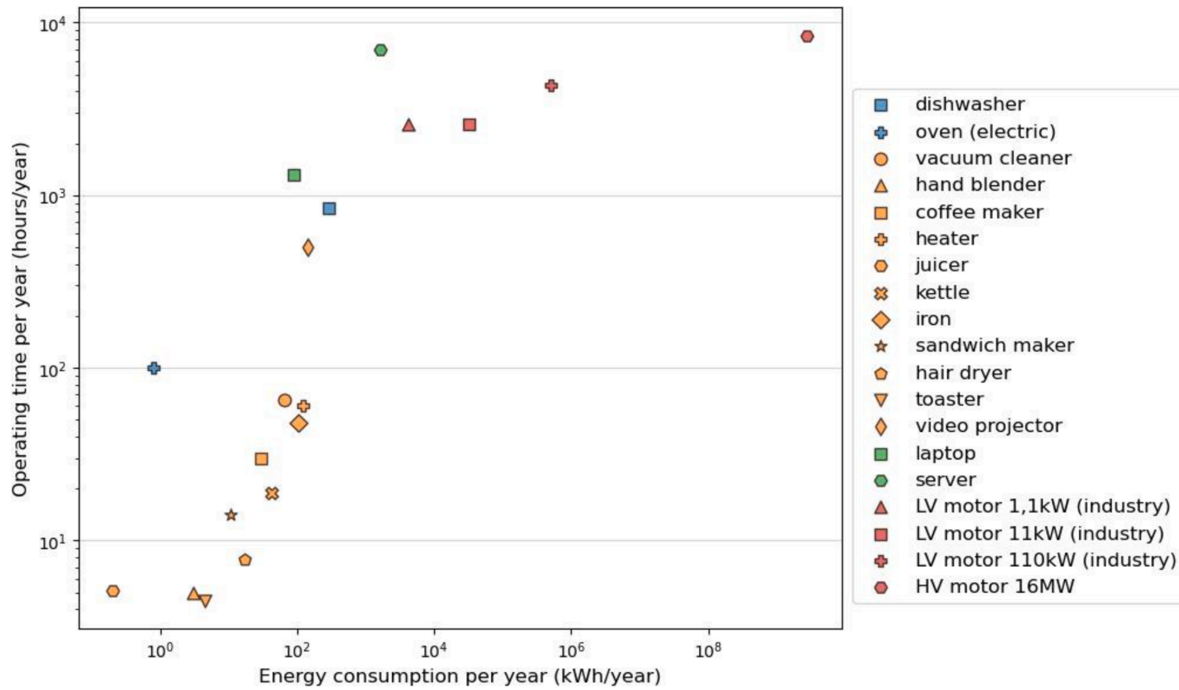

Fig. A.2. Comparison of the annual energy consumption and operating time of different EuP (logarithm scale). Data are from the same sources as for Fig. A.1.

intensive use need to be included for use extension to be beneficial.

Regarding the inclusion of requirements promoting use extension in the European Ecodesign directive and similar policy initiatives, efforts should be channelled on ensuring high energy efficiency by design for EuP with intensive and long use. Furthermore, in case of slow development of energy efficiency, ensuring a more durable design would be more relevant than repair which would lead to little benefit while risking impairing the product's energy efficiency performance. Prioritising these efficient and durable designs as well as ensuring proper maintenance of energy efficiency would benefit users of energy intensive EuP.

Finally, the use of resources for electricity production and

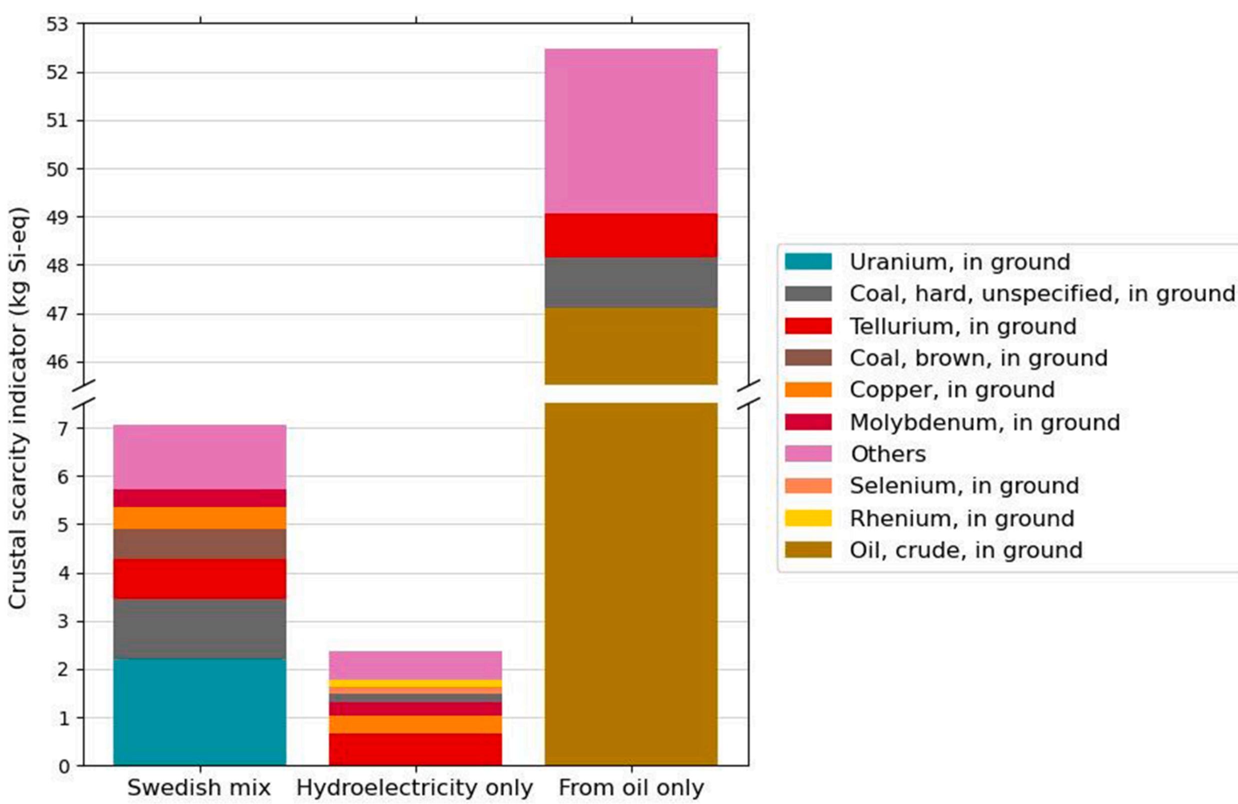

Fig. B.1. Contribution of elementary flows to the CSI of the production of 1 kWh of electricity from the Swedish electricity mix (left), hydroelectricity only (middle) and from oil only (right).

transmission is as important as the resources in the product. Instead of a trade-off between resource and energy efficiency with the more energy-efficient design being more resource intensive as in other studies, energy efficiency also leads to a reduction of resource depletion impact. This highlights the importance of including resource use from electricity production and transmission when exploring CE strategies, especially for energy intensive EuP.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2023.107038.

Appendix A. Comparison of the intensity of use for various energy using products

Fig. A.1.,Fig. A.2.

Appendix B. Contribution of elementary flows to resource depletion for electricity production

Fig. B.1.

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