Assessing the environmental impacts of policies on industrial electric motors: a stock model, material flow analysis and life cycle assessment approach

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Abstract

Electric motors are significant contributors to energy consumption in the EU, accounting for more than half of the total electricity consumed. In order to reduce the environmental impact, there is a need to address the inefficiency of existing motors. This study explores how early replacement of inefficient motors can reduce environmental impacts at the system level and compares this strategy with a base case. A combined material flow analysis and life cycle assessment approach is used to provide answers. Using a layered approach, material and environmental impacts are derived from product flows through a product database that defines physical properties for different product variants. The study focuses on industrial electric motors in the EU and employs a scenario analysis from 2005 to 2050 to assess the long-term impacts of different policy alternatives. Specifically, the environmental impacts of early replacement of IE2 and IE3 motors with IE4 motors are compared to minimum energy performance standards and to a base case scenario with no change. This comparative analysis aims to highlight the potential environmental benefits of implementing different policy measures beyond mere energy savings. The results of this study have implications for sustainability and energy efficiency policies in the EU. By understanding the environmental impacts of different policy measures on industrial electric motors, policy makers and industry stakeholders can make informed decisions to promote sustainable practices and reduce energy consumption in the long term.

Introduction

Motors account for a large share of the electricity consumption: 30 % is used in industrial electric motor-driven systems in the world (IEA 2016) and around 50 % in the EU (European Commission 2019a). At the same time, new motor technologies are very efficient, such as IE4 class and IE5 class motors, which are the highest international energy efficiency classes according to the IEC 60034-30-1 standard.

Backed by the more efficient motor technologies, there are two main approaches to reduce electricity consumption of the motor stock: the first one consists of improving the performance of new motors placed on the market (European Commission 2019a), the second one consists of replacing inefficient motors earlier than companies would normally do. Accordingly, motors are subject to Minimum Energy Performance Standards (MEPS) to push and incentive programs to pull the global motor market towards high efficient motors. The Collaborative Labeling and Appliance Standards Program (CLASP) identified 43 MEPS regulations for motors and motor driven equipment adopted around the world (CLASP 2024), and UNEP is promoting energy efficiency requirements with its model regulation guidelines (UNEP 2019). In the EU, the energy efficiency of motors has been regulated since 2011 within the Ecodesign framework (European Commission 2009), and this regulation has been recast in 2019 (European Commission 2019a). In addition, there are several programs in EU Member States to replace old motors by more efficient one's (Enerdata 2024).

While the advantage of both approaches (improving efficiency of new motors or replacing inefficient one's earlier) in terms of energy consumption is obvious, the overall environmental impacts are less clear or even unknown. Within the Green Deal (European Commission 2019b), the EU product policy framework is focusing not only on energy efficiency but on a more holistic approach. The Circular Economy Action Plan (CEAP) 2020 (European Commission 2020) and the forthcoming Ecodesign for Sustainable Products Regulation (ESPR) (European Commission 2022) highlight the great importance of circular economy approaches and the overall environmental impacts of products. The ESPR is the recast of the Ecodesign framework, expanding the scope beyond energy-related product and with the aim to foster circular economy and sustainability.

To support the understanding of motor policy impacts, this paper aims to answer the following research questions: 'How to quantify the environmental impacts of the transformation of the EU electric motor market?' and 'Which environmental benefits beyond saving energy can be expected from early replacement of old motors, stricter ecodesign requirements for new motors or a combination of both approaches?'.

Methodology

EXISTING POLICIES

The EU27 market for industrial electric motors has already been regulated by two generations of ecodesign regulations: (EC) No 640/2009 and (EU) 2019/1781. The regulations include several requirements that are relevant for this analysis. The main requirements are:

- (EC) No 640/2009 of July 2009 for ecodesign requirements for electric motors (European Commission 2009):
  - "from 16 June 2011, motors shall not be less efficient than the IE2 efficiency level;
  - from 1 January 2015: motors with a rated output of 7.5–375 kW shall not be less efficient than the IE3 efficiency level […] or meet the IE2 efficiency level […] and be equipped with a variable speed drive;
  - from 1 January 2017: all motors with a rated output of 0.75–375 kW shall not be less efficient than the IE3 efficiency level […] or meet the IE2 efficiency level […] and be equipped with a variable speed drive"
- (EU) 2019/1781 of October 2019 repealing (EC) No 640/2009 (European Commission 2019a):
  - "from 1 July 2021:
    - the energy efficiency of three-phase motors with a rated output equal to or above 0,75 kW and equal to or below 1 000 kW, with 2, 4, 6 or 8 poles, which are not Ex eb increased safety motors, shall correspond to at least the IE3 efficiency level […];
    - the energy efficiency of three-phase motors with a rated output equal to or above 0,12 kW and below 0,75 kW, with 2, 4, 6 or 8 poles, which are not Ex eb increased safety motors, shall correspond to at least the IE2 efficiency level […];"
  - "from 1 July 2023:
    - the energy efficiency of Ex eb increased safety motors with a rated output equal to or above 0,12 kW and equal to or below 1 000 kW, with 2, 4, 6 or 8 poles, and single-phase motors with a rated output equal to or above 0,12 kW shall correspond to at least the IE2 efficiency level […];
    - the energy efficiency of three-phase motors which are not brake motors, Ex eb increased safety motors, or other explosion-protected motors, with a rated output equal to or above 75 kW and equal to or below 200 kW, with 2, 4, or 6 poles, shall correspond to at least the IE4 efficiency level […]."

According to Art. 9 of (EU) 2019/1781, the regulation was due to be evaluated and reviewed by 14 November 2023. As of January 2024, the review process has not yet started but is expected to start soon. More stringent energy efficiency requirements are likely to be defined and the recast might be carried out within the forthcoming ESPR framework.

MODEL CHARACTERISTICS

The underlying multi-dimensional model was developed by researchers at Fraunhofer ISI for application in Ecodesign preparatory studies or impact assessments (extending previous models such as those used in (Hirzel et al. 2011) or (van Tichelen et al. 2019)) with the following features:

- it combines an analysis of product stock, material flows and environmental impacts for different product variants (design options),
- while the former model considered only measures on new products placed on the market to be in line with the Ecodesign and Labelling framework, the new model can cover measures that affect the lifetime of motors in the product stock (such as early replacement),
- it includes up to 16 environmental impact categories (e.g. based on data from the EcoReport Tool (European Commission 2013) or a PEF study (European Commission 2010)). Furthermore, energy and material consumptions can also be analysed,
- it considers up to seven life stages (from raw materials to end-of-life) of the product.

Figure 1 shows the basic structure of the model.

ASSUMPTIONS

For the purpose of this paper and to show a first example of application, the following assumptions have been considered in the scenarios:

- the product scope was set to electric motor within 0.75–7.5 kW power class range (for which MEPS are the leat stringent)
- sales and stock volumes: based on the Ecodesign preparatory study on motors (Almeida et al. 2008)
- bill of materials of electrical motors were based on the preparatory study (Almeida et al. 2008) for motors with efficiency classes IE2, IE3 and IE4. No VSD were considered
- Life cycle analysis (LCA) data were generated with the EcoReport Tool 2014 version (European Commission 2013)

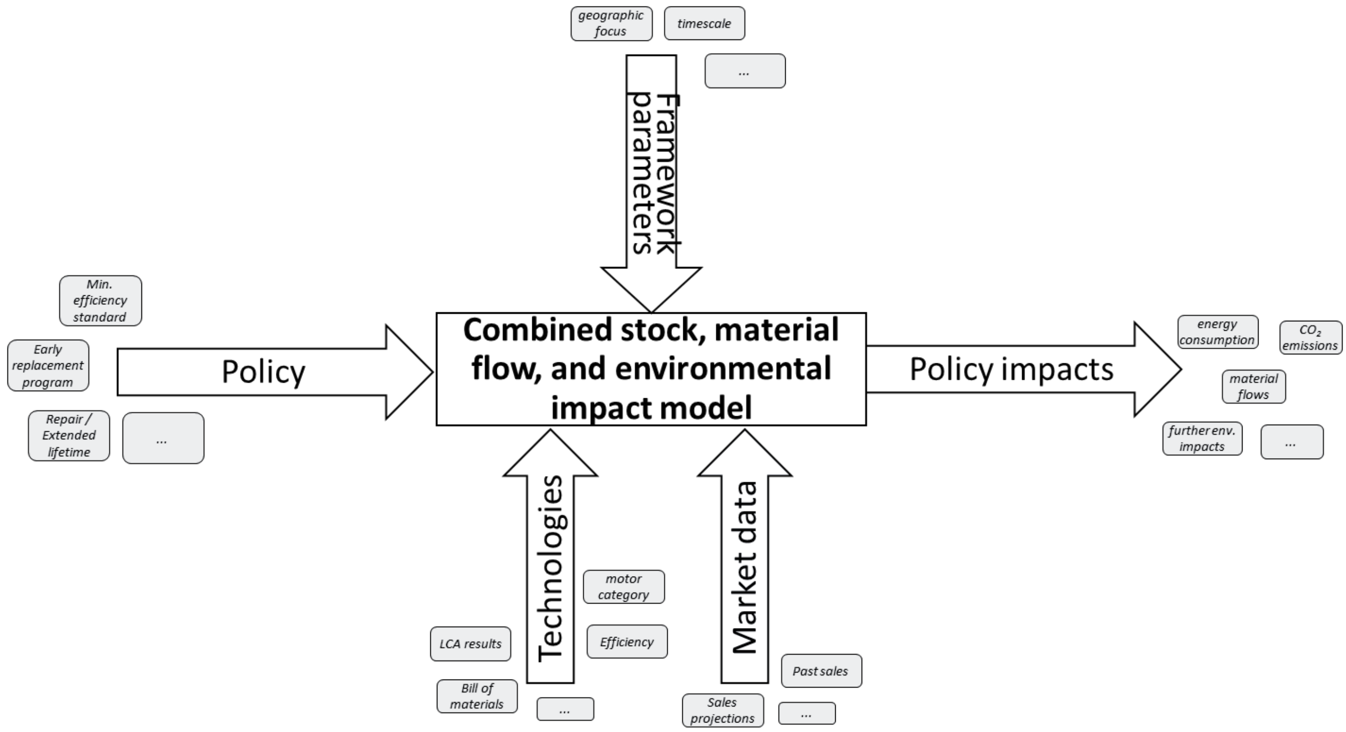

Figure 1. Overview of the structure of the model.

- the life stages are the same as those considered in the EcoReport Tool
- the market share by energy efficiency class until end of 2025 was based on the preparatory study (Almeida et al. 2008) and preliminary results of the EU-MORE market study (ISR-University of Coimbra 2024)
- the following policies were considered:
  - BAU: no new policy, but a slow shift towards IE4 motors is assumed until 2050 (no frozen efficiency scenario)
  - Replace: from 1.1.2025, all IE2 motors in the stock will be replaced 4 years earlier than the original lifetime (12 years) by new motors that meet the ecodesign requirements in the given year.
  - MEPS: from 1.1.2025, new motors must comply with new ecodesign requirements, it is assumed that IE4 would be mandatory.
  - MEPS_Replace: combination of both policies. From 1.1.2025, all IE2 motors in the stock will be replaced with new IE4 motors after 8 years.

Results

IMPACT ON ENERGY CONSUMPTION

Figure 2 shows the energy consumption during the use phase. Although the EU stock increases by 34 % between 2005 and 2025, the electricity consumption for the operation of the motors increases by only 15 % in the first 10 years and then remains almost constant at 21 TWh/a. This is thought to be mainly due to the Ecodesign requirements introduced from 2011 onwards, which have accelerated the market transformation towards energy efficient motors, as shown in Figure 3. Other policies (e.g. mandatory energy audits) have also contributed to replace inefficient motors by better one's.

Based on the model results, the energy consumption of the stock is expected to remain constant in the BAU scenario from 2025 to 2050, while the stock is expected to increase by a further 15 %. The IE4 requirements in the MEPS scenario lead to a significant reduction of the energy consumption (21 TWh) within 12 years, which corresponds to the assumed lifetime of motors in this power range. Replacement programs lead to a moderate and temporary decrease in electricity consumption (2 TWh), as they affect motors sold between 2017 and 2025, which are already subject to the first ecodesign requirements.

IMPACT ON MATERIAL DEMAND

Table 1 shows typical results from the material-flow-analysis which can be generated by the model.

As the copper and aluminium content in IE4 motors is higher than in IE3 or IE2 motors, the MEPS scenario leads to an increase in demand in both scenarios compared to the BAU scenario. In both scenarios, including early replacement, there is a short peak in material demand (around 30 %) for aluminium and copper, but the effect is limited (less than 2 %) when considering the whole period 2026–2050.

ENVIRONMENTAL IMPACTS

In addition, the model can estimate the environmental impacts at scenario level. Table 2 shows the impacts normalised to EU totals for GHG emissions (measured before normalisation in kg $CO2_{eq.}$) and acidification (measured before normalisation in

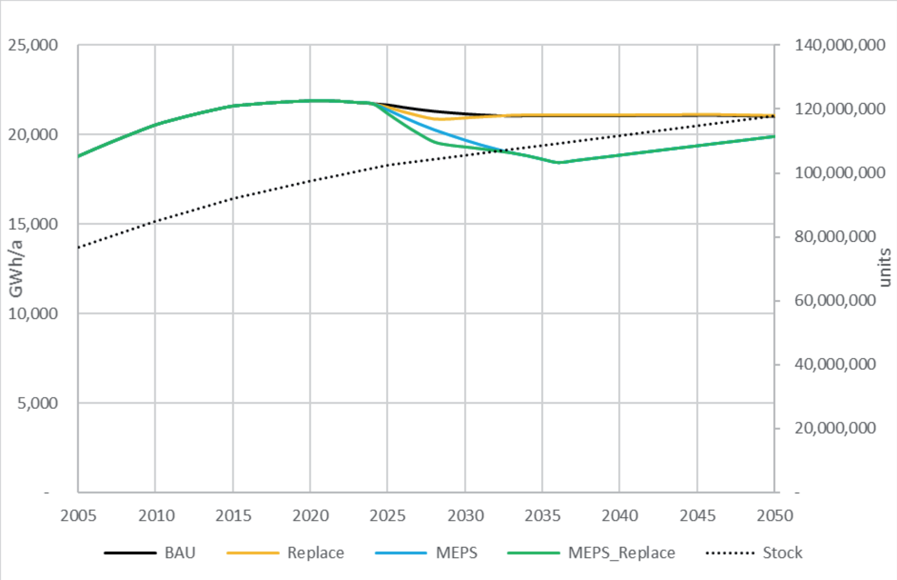

Figure 2. Electricity consumption in the use phase whole EU27 stock.

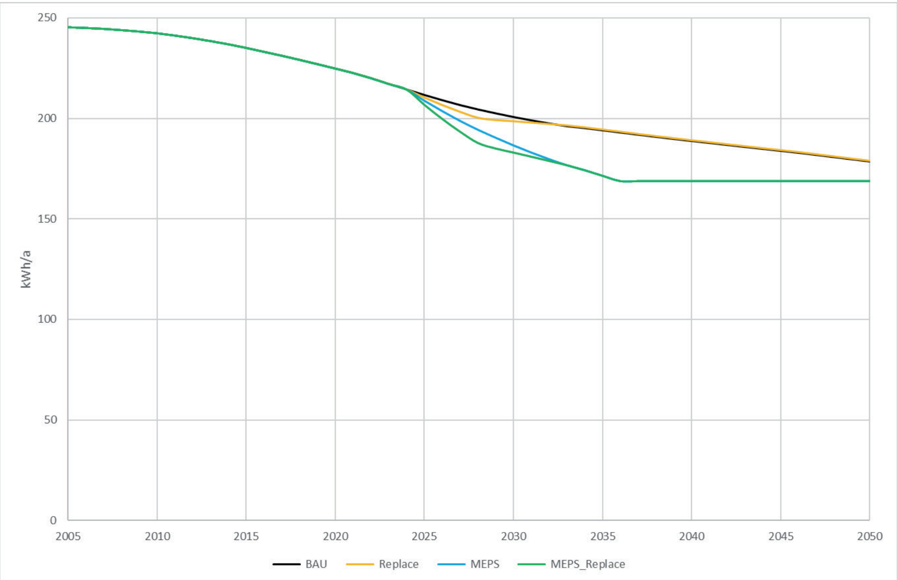

Figure 3. Specific electricity consumption of an average motor in the EU27 stock.

Table 1. Amount of material entering the market, in the stock and leaving the market.

		Entering the market			In the stock			Leaving the market		
		2005	2025	2026–2050	2005	2025	2026–2050	2005	2025	2026–2050
Aluminium	BAU [t]	4,827	8,363	218,896	53,734	84,375	2,480,283	3,816	6,538	191,867
	Replace [–]	+0 %	+28.9 %	+0.8 %	+0 %	+0.6 %	0.1 %	+0 %	+29.7 %	+1.3 %
	MEPS [–]	+0 %	+12.5 %	+6.4 %	+0 %	+1.2 %	6.5 %	+0 %	+0.0 %	+5.7 %
	MEPS_Replace [–]	+0 %	+45.0 %	+7.5 %	+0 %	+2.2 %	6.9 %	+0 %	+29.7 %	+7.3 %
Copper	BAU [t]	14,531	30,069	831,453	160,556	289,734	9,206,298	11,394	20,884	688,185
	Replace [–]	+0 %	+28.9 %	+0.7 %	+0 %	+1.0 %	0.2 %	+0 %	+27.8 %	+1.4 %
	MEPS [–]	+0 %	+25.5 %	+12.3 %	+0 %	+2.6 %	12.8 %	+0 %	+0.0 %	+11.6 %
	MEPS_Replace [–]	+0 %	+61.7 %	+13.5 %	+0 %	+4.4 %	13.6 %	+0 %	+27.8 %	+13.7 %

Table 2. Normalized environmental impacts of motors, for the impact categories GHG emissions and acidification.

		2005	2025	2026–2050	2005	2025	2026–2050
GHG [–]	BAU	1,853	2,143	51,588	1,853	2,143	1,588
	Replace		2,178	51,501	+0.0 %	+1.6 %	-0.2 %
	MEPS		2,152	47,414	+0.0 %	+0.4 %	-8.1 %
	MEPS_Replace		2,190	47,142	+0.0 %	+2.2 %	-8.6 %
Acidification [–]	BAU	1,968	2,394	58,058	1,968	2,394	58,058
	Replace		2,504	57,994	+0.0 %	+4.6 %	-0.1 %
	MEPS		2,489	54,712	+0.0 %	+4.0 %	-5.8 %
	MEPS_Replace		2,626	54,488	+0.0 %	+9.7 %	-6.1 %

g $SO_{2eq.}$) generated annually by motors entering or leaving the market in a given year, as well as the operating phase of motors in the stock.

Discussion

LOGIC OF THE MODEL

The model can deal with a variety of environmental impacts and can generate results that provide information on material flows, environmental impacts for different life stages and various type of measures. In addition to MEPS, measures impacting the lifetime of products (such as early replacement or repair) can be covered. Measures related to recycling or recycled content could also be covered if included in the environmental analysis, although they are not presented in this paper. The model therefore goes beyond the existing approach for the impact assessment under the Ecodesign framework, both in terms of the measures/policies covered and the outputs available for analysis. Due to the increased number of input data, life cycle stages and impact categories considered, the amount of data to be processed is in the order of 100 times larger than in a common ecodesign stock model.

QUALITY OF THE RESULTS

The quality of the results depends on the quality of the input data and of the type of environmental assessment carried out. Having considered the bill of materials of (Almeida et al. 2008) for the example of this paper, industrial motors were analysed without contents of rare earths elements, although critical raw materials are nowadays considered as very relevant in the Ecodesign context (Viegand Maagøe, VHK, Fraunhofer ISI 2023). The analysis of material flows becomes even more important when analysing permanent magnet motors using materials such as neodymium and dysprosium, where supply risks are high and resource efficiency can help to reduce import dependencies.

INTERPRETATION OF THE RESULTS

Challenges arise when interpreting the results. In particular – and this is often the case – when a measure reduces environmental impact in some categories but increases the impact in other categories. In such a case, it is difficult to assess the "best" measure to consider. One solution would be to perform a multi-criteria analysis. For environmental impact, this usually means generating a single score by weighting and summing the normalised environmental impacts. Such an approach is not implemented in the current EcoReport Tool (even though a normalization of the environmental impact categories to EU totals is available). The ongoing revision of the EcoReport Tool will align the impact categories with those of the Product Environmental Footprint (PEF) method (European Commission 2010). For the PEF categories, researchers from the Joint Research Institute have proposed a common weighting approach (SALA et al. 2017), but as they themselves state, any weighting scheme "is not mainly natural science based but inherently involves value choices that will depend on policy, cultural and other preferences". In addition, the state of knowledge and the associated uncertainties for the different impact categories vary widely.

Assessing the results in this study is more complicated than in previous ecodesign assessments. Some impacts occur when the product enters the market, others during its use phase or at the end of its life. Accordingly, measures with end-of-life impacts will generate costs from the first year of implementation but will deliver benefits (in terms of environmental impact) much later, while energy efficiency measures (e.g. parameter setting of the product) alone will deliver continuous energy savings throughout the life of the product.

POTENTIAL OF IMPROVEMENTS

In terms of logic, the model already functions well. The main potential for improvement remains in its usability, which can be further optimised by simplifying the management of input and output data, as well as the flexibility of the model to compare a large number of scenarios. One way of dealing with the complexity of the model and the amount of data to be processed would be to switch from MS Excel to a more powerful modelling environment (e.g. Python). The economic dimension is not yet covered in this version of the model but can easily be included and treated in the same way as an additional impact category.

Conclusion

This paper has briefly presented how a comprehensive bottom-up combined stock, material flow and environmental impact model can be used to assess the impact of a wide range of energy and resource efficiency policies, with a case study on electric motors. Preliminary results show that, for the motor range considered, IE4 requirements for new motors would deliver 44 TWh (8 %) of electricity savings over the period 2026–2050 compared to the BAU scenario, but would increase the demand for aluminium and copper by 6 % and 12 % respectively. Environmental impacts for the categories GHG and acidifications would decrease by 8 % and 6 % respectively. Combined with a replacement program for old motors, IE4 requirements would lead to 3 TWh of additional energy savings and contribute to a slight reduction of the environmental impacts of the aforementioned categories, but increase the demand for aluminium and copper by around 1 %. A simple replacement program of old motors is expected to have a limited impact in the selected categories, as it would target a limited number of motors for the selected power range.

While the impact of the policies can be assessed in terms of material flows and for the different impact categories, assessing the overall impact is a more challenging exercise. Accordingly, no overall environmental impact is presented here. However, this problem is not inherent to the stock model itself but rather to the environmental assessment carried out and used as input for the model. The 2014 version of the EcoReport Tool was used for this paper. In principle, the model could be used with the revised EcoReport Tool (when available) or results of PEF studies, which could facilitate the interpretation of the results of the environmental analysis and even allow the calculation of a single score. Nevertheless, our study already helped to better identify and understand the trade-offs between improving energy efficiency and reducing the environmental impact of products.

Further developments of the model are ongoing to improve the user interface as well as the flexibility to deal with other product groups and multiple scenarios, as this type of model is not only relevant for the presented case study but would also be useful for preparatory studies and impact assessments for other products in the context of the forthcoming ESPR Regulation.

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