# Motor Design Strategies in View of the EU Ecodesign Revision

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**Abstract.** The process of revising the EU Ecodesign regulation on motors is ongoing, with stricter energy performance standards and material efficiency requirements on the agenda. How exactly the revised regulation will take shape is still uncertain, but the upcoming combination of energy efficiency requirements and material use restrictions are likely to present motor manufacturers with unprecedented challenges. The precise nature of these challenges will largely depend on the way material efficiency is formulated. Material masses are likely to be differentiated according to their criticality, while recyclability could also be regulated. Material use could also be considered in a broader perspective: increasing the energy efficiency of electric motor systems reduces the generation capacity required to cover the energy losses, leading to an associated reduction in material use and improving the overall environmental balance. This paper presents some design options to contend with possible future requirements.

**Keywords:** energy efficiency, resource efficiency, Ecodesign, MEPS, alternative winding techniques, copper rotor motor, rare earth materials, recyclability

## 1 The Upcoming EU Ecodesign Regulation Revision

The process of revising the EU Ecodesign regulation on motors is ongoing, leading to a proposal for a new regulation to come in 2025. Article 9 of the regulation stipulates the matters to be addressed, including the introduction of stricter minimum energy performance standards (MEPS), an extension of MEPS to also incorporate permanent magnet motors, and the introduction of resource efficiency requirements in accordance with circular economy principles. The latter issue should be viewed in the context of the ongoing evolution of the existing Ecodesign Directive to become the Ecodesign for Sustainable Products Regulation (ESPR), which will take a broader set of environmental impact categories into account.

How exactly the revised regulation will take shape is still uncertain, but the upcoming restrictions are likely to present motor manufacturers with unprecedented challenges. The potential introduction of stricter MEPS does not pose major design problems in itself, since some induction motors available on the market today already meet IE4 efficiency requirements. Combining increased efficiency levels with a reduction in material mass, however, is a totally different kind of challenge.

In the next section we discuss the options for further enhancing motor efficiency while taking account of circular economy principles.

## 2 Design Options to Improve Energy Efficiency

The most straightforward option improving induction motor efficiency is increasing the stator windings cross-section. This would also increase the mass of electrical steel and structural steel. This increased use of material to improve motor efficiency means that less material will be used for the power generation capacity needed to cover the motor losses—we discuss this in Section 5.

There are strategies, however, to increase the energy efficiency of induction motors without increasing their mass. One of the most effectively uses superior electrical steel and thinner steel laminations for the stator core. Other potential measures include improving the cooling mechanism and reducing bearing friction. Many efforts have been made already in this respect, which means there is now limited scope for developing them further. In recent years, alternative winding techniques have emerged as an effective way to enhance the efficiency of a motor without increasing its size—we discuss this in Section 3. A totally different kind of strategy is to switch from an aluminium rotor to a die-cast copper rotor—this is discussed in Section 4.

The efficiency of an electric drive system can also be enhanced by switching to an alternative motor technology. For fixed speed operation, squirrel-cage induction motors remain the preferred choice for reasons of cost and reliability, but in cases where a variable speed drive (VSD) is required, other motor technologies come into the same price range. Synchronous reluctance motors (SynRM), permanent magnet synchronous motors (PMSM) and axial flux motors have intrinsically higher efficiency due to their operation at synchronous speed, almost entirely eliminating rotor losses. Losses are further reduced because synchronous motors have higher efficiency under partial load.

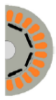
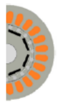
| Indicator/Feature | Self-Cooled Three-Phase Radial-Flux Motor Technology | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Variable-Speed Applications (Optimized Supply Voltage and Frequency) | | | | Fixed-Speed Applications (Rated Supply Voltage and Frequency) | | | |
| | SCIM | PMSM | SynRM | PMSynRM | SCIM | Line-Start PMSM | Line-Start SynRM | Line-Start PMSynRM |
| Cross-sectional topology with identification of active materials:<br>• orange areas: copper<br>• light grey areas: aluminum<br>• dark gray areas: steel<br>• black areas: permanent magnets |  |  |  |  |  |  |  |  |
| Line-start capability without VSD | yes | no | no | no | yes | yes | yes | yes |
| Requires VSD | yes | yes | yes | yes | no | no | no | no |
| Possibility of using an electronic soft-starter or Y-D starter | n.a. | n.a. | n.a. | n.a. | yes | no | no | no |
| Motor cost | $ | $$$ | $ | $$ | $ | $$$ | $$ | $$ |
| VSD cost | $ | $ | $$ | $ | n.a. | n.a. | n.a. | n.a. |
| Rated efficiency of the motor (best available technology) | ••• | ••••• | •••• | •••• | ••• | •••• | ••• | •••• |
| Typical efficiency class range | IE1–IE4 | IE4–IE5 | IE3–IE5 | IE4–IE5 | IE1–IE4 | IE3–IE4 | IE3–IE4 | IE4–IE5 |

**Fig. 1.** Comparison of motor technologies (Source: [1])

All these motor types come with drawbacks, however. PMSMs are more costly to manufacture, and axial flux motors cost even more. Both PMSMs and axial flux motors make use of permanent magnets (PMs) usually fabricated using rare earth metals, which entails a supply risk and will probably be discouraged in the upcoming regulation (see Section 6). PMs can also be fabricated using ferrite, but this reduces the flux density, resulting in a higher motor volume. Synchronous reluctance motors do not use rare earth metals and are less costly than PMSMs, but always need an electronic drive, making them economically attractive only for variable speed applications.

## 3 Alternative Stator Winding Techniques

Energy efficiency improvement in induction motors can largely be uncoupled from additional material use through alternative winding techniques that increase the slot fill factor in stator windings, defined as follows:

$$\textit{Slot fill factor} = A_w/A_s \quad (1)$$

where $A_w$ is the area of the wire sections, and $A_s$ the area of the slot section.

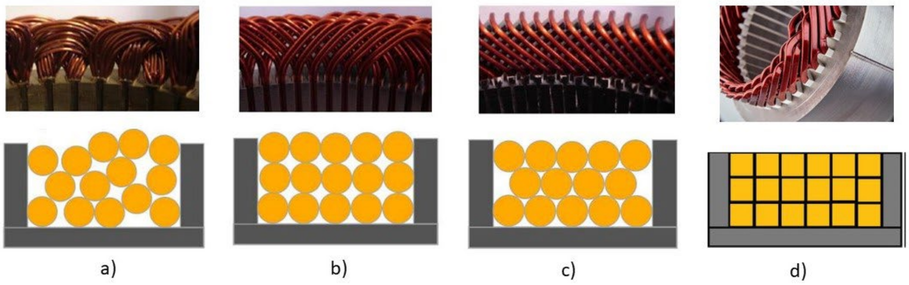



**Fig. 2.** Four winding configurations: a) round wires, random, b) round wires, on top of each other, c) round wires, orthocyclic layers, and d) rectangular wires.

Fig. 2 illustrates four different winding configurations with progressively increasing slot fill factors. Random winding (Fig. 2a) is the most frequent in large-scale motor production with automated processes, but results in a low slot fill factor, typically below 55%. Placing the windings on top of each other (Fig. 2b) will increase the slot fill factor. The optimal configuration for round wires is orthocyclic layer winding (Fig. 2c), which can attain a slot fill factor of up to 75%, but the production process for such a configuration requires special equipment. Even higher slot fill factors can be reached by using rectangular wire sections. With this technique, the slot can be filled entirely by conductors and dielectric material, resulting in slot fill factors of up to 85% [2] .

Increasing the slot fill factor has several advantages. It increases the amount of copper in the stator, which reduces the electrical resistance and consequently the energy losses. This is achieved without the need to increase the frame size, which means that the amounts of structural steel and electrical steel remain the same. Increasing the slot fill factor will also optimize the interaction between the conductors and the magnetic field, maximizing the electromagnetic energy conversion and minimizing the magnetic losses. Furthermore, it reduces the amount of dielectric material between the conductors, allowing for more efficient heat transfer. All these elements combined result in an energy efficiency improvement with a minimum of additional material.

The use of rectangular wires is often combined with hairpin windings [3]. With this technology, the conductor segments are pre-formed into hairpin-like shapes to fit precisely within the stator slots. Once inserted, the hairpin ends are bent and the hairpin segments are connected to each other by welding. By using hairpin windings, more copper can be fit into the same space, which translates into a reduction of the stator core length and, therefore, a reduction in electrical steel use. The use of hairpin windings also reduces the amount of inactive copper extending beyond the stator core, which means that less material is needed without affecting the energy efficiency.

## 4 The Die-cast Copper Rotor Motor

Because copper has superior electrical conductivity, switching from aluminium to copper as a conductor in the rotor will reduce losses while maintaining the same motor size. The die-cast copper rotor first appeared on the market around 25 years ago and has been perfected in recent years, spurred by the interest of electric vehicle manufacturers [4]. The technical challenges that come with die-casting copper have meanwhile been overcome by a number of companies supplying reliable and high-quality rotors.

Aside from efficiency and compactness, these motors have other advantages, of which robustness is probably the most important—allowing them to withstand the centrifugal pressure that comes with high-speed applications [5], [6]. This robustness follows from the higher mechanical strength of copper compared to aluminium and the higher die-cast temperature, which enhances the mechanical strength of the steel.

Copper has a higher density than aluminium and costs more weight for weight, but this price premium is partly compensated by savings in other materials, such as electrical and structural steel. These material savings result from the fact that a copper rotor motor is smaller than its aluminium counterpart if all other parameters (including the energy efficiency) are kept the same. In certain power ranges and for certain types of applications, swapping aluminium for copper as a rotor conductor can be a competitive option to enhance energy efficiency.

## 5 Material Balance at System Level

When evaluating the trade-off between material use and energy efficiency, it should be kept in mind that energy losses necessitate additional power generation capacity, which also comes with material use.

Let us consider swapping an 11 kW IE3 motor (4-pole, 50 Hz) for its IE4 equivalent. The bills-of-material in the Ecodesign preparatory studies indicate that such an efficiency upgrade would lead to an additional 30 kg of metals being used to manufacture the motor [7], [8]. The energy efficiency improves from 91.4% to 93.3% [9], resulting in an energy loss reduction of 245 W, or 0.86 MWh per year when assuming an annual running time of 3500 hours (full load equivalent). The generation capacity needed to cover this difference in energy losses implies material use. Assuming the electricity mix between 2025 and 2045 to evolve as projected in the EU Green Deal Impact Assessment [10], it is possible to derive the figures for material use per type of generation capacity from the US Department of Energy's 'Renewable Energy Materials Properties Database' [11]. If we further assume an annual productivity of 2076 hours (full load equivalent) and a lifespan of 20 years for onshore wind turbines, an annual productivity of 3214 hours (full load equivalent) and a lifespan of 25 years for offshore wind turbines, and an annual productivity of 1200 hours (full load equivalent) and a life span of 25 years for solar PV plants [12], we can calculated that 1 MWh of energy losses per year corresponds with 150 kg of metals used for generation capacity. Consequently, the annual energy savings of 0.86 MWh associated with a switch from an IE3 motor to an IE4 unit saves 129 kg of metals in generation capacity, or more than four times the additional metal use in the motor itself.

# 6 Criticality and Recyclability of Motor Materials

## 6.1 The Criticality and Impact of Rare-earth PMs

The PMs used in some motor technologies, though not ferrite magnets, contain rare earth elements (REEs), as previously discussed. REE PMs are composed of a neodymium-iron-boron (NdFeB) alloy with the addition of dysprosium (Dy) to increase the temperature range that avoids demagnetization.

The use of REEs such as neodymium and dysprosium bring with its price volatility and supply chain risk, since exploitable ore deposits are scarce and geographically concentrated [13]. The European Commission formalized these and other concerns in the Critical Raw Materials Act, which seeks to make the energy transition in the EU less dependent on using imported critical raw materials. It aims to achieve this by supporting the development of substitution technologies while, at the same time, stimulating the extraction, processing, and recycling of materials present in the EU domestically.

The use of neodymium and dysprosium also has a high environmental impact. Their extraction and processing are energy and carbon intensive [14], while landfilling PMs poses environmental risks due to the potential leaching of these metals, which are harmful to soil and groundwater ecosystems [15].

Both the criticality and environmental impact of rare-earth PMs could be mitigated by developing domestic recycling routes. Efficient and integrated recycling routes are currently lacking, partly because the quantities reaching end-of-life remain small, but also because of technical barriers [16]. In the future, the need for REEs in the electric vehicle and renewable energy industries could stimulate the development of recycling technologies and create a business model for recycling routes [17]. Until recycling routes are available, EU policies will continue to discourage the use of REEs.

## 6.2 The Recyclability of Copper, Aluminium and Electrical Steel

Improving the energy efficiency of induction motors usually comes with an increase in the use of copper, aluminium, and electrical steel.

The copper used in motor windings is highly recyclable. After recovery, the great majority can be recycled at purity level 1A, which means that it has the same quality as copper cathodes. It can be melted and used again for electrical applications, including motor windings, without further purification. This means that it follows a circular route that is highly efficient in terms of cost, energy use, and environmental impact. Even if copper windings get mixed with other, less pure recycled copper streams, it is still possible to achieve purity level 1A by further processing the material in primary or secondary smelters.

The aluminium used in squirrel-cage rotors can be almost entirely recovered for recycling. In theory, it could be recycled with purity levels of up to 99.7%, which is the level required for re-use in electrical aluminium. In practice, the fact that aluminium exists in many different alloy forms constitutes a barrier. The material could be subjected to laboratory analysis to detect the alloy composition and then be recycled for use only in the same kind of application. Currently, recycling companies consider this too complicated, with the material downgraded for use in second-life products for which lower purity is sufficient.

The electrical steel from motors could, in theory, be recycled entirely for use in the same application, but this is complicated by practical barriers. The main issue is the presence of silicon, which is added to mitigate hysteresis and eddy current losses in the motor core [18]. The market for silicon steel is limited to motors, transformers, and some other electrical equipment. Moreover, motors use non-grain-oriented steel, while transformers require grain-oriented steel, meaning that these two recycling streams should be kept separate [19]. For all these reasons, electrical steel is mixed as scrap for the production of less noble steel. Only small quantities of silicon steel can be added to each melting batch without compromising the process [20].

## 7 Conclusions

The process of revising the EU Ecodesign regulation on induction motors is ongoing. If more stringent MEPS would be adopted, this would lead to substantial electricity savings in the EU, but also to an increased material use in motor manufacturing. Indeed, the most straightforward option improving induction motor efficiency is increasing the stator windings cross-section. Some technology routes could mitigate this trend, including alternative winding techniques, a switch from aluminium to copper as a rotor conductor material, and the use of alternative motor technologies.

Apart from that, policy makers also have a reason to be indulgent when it comes to additional material use in motors if it leads to greater energy efficiency. In the broader picture, energy losses also entail material use, since they require additional power generation capacity. This material use at system level is likely to be greater than the additional material required to enhance motor efficiency, as we demonstrated with an example.

Moreover, the goal of the circular economy is not to reduce material mass as such, but rather to reduce the environmental impact and geopolitical risks that come with material use. In this respect, the criticality and recyclability of materials used in motor manufacturing should receive full attention.

We conclude that solutions are available, as long as material mass is not taken as an absolute criterion.

## References

[1] A. T. de Almeida, F. J. T. E. Ferreira, and J. Fong, "Perspectives on Electric Motor Market Transformation for a Net Zero Carbon Economy," *Energies (Basel)*, vol. 16, no. 3, 2023, doi: 10.3390/en16031248.

[2] A. Arzillo *et al.*, "Challenges and Future opportunities of Hairpin Technologies," in *2020 IEEE 29th International Symposium on Industrial Electronics (ISIE)*, 2020, pp. 277–282. doi: 10.1109/ISIE45063.2020.9152417.

[3] A. Arzillo *et al.*, "Challenges and Future opportunities of Hairpin Technologies," in *2020 IEEE 29th International Symposium on Industrial Electronics (ISIE)*, 2020, pp. 277–282. doi: 10.1109/ISIE45063.2020.9152417.

[4] N. Riviere, M. Villani, and M. Popescu, "Optimisation of a High Speed Copper Rotor Induction Motor for a Traction Application," *IECON Proceedings (Industrial Electronics Conference)*, vol. 2019-Octob, pp. 2720–2725, 2019, doi: 10.1109/IECON.2019.8927627.

[5] R. Tiwari and A. K. Bhardwaj, "Analysis of Induction Motor with die cast rotor," *International Journal of Innovative Research in Electrical*, vol. 2, no. March, pp. 2321–5526, 2014, [Online]. Available: www.ijireeice.com

[6] A. Bárdos, C. Walczer, Z. Kéri, and I. Selmeczi, "Copper Rotor Technology for High Efficiency Motors," in *Vehicle and Automotive Engineering 2*, K. Jármai and B. Bolló, Eds., Cham: Springer International Publishing, 2018, pp. 186–198.

[7] A. T. de Almeida, H. Falkner, João Fong, and K. Jugdoyal, "EuP Lot 30 : Electric Motors and Drives. Task 1: Product Definition, Standards and Legislation," Brussels, 2014.

[8] J. Fong. de Almeida AT, Fonseca P, Fernando J T E Ferreira, "EUP Lot 11 Motors - Final." Accessed: Apr. 06, 2020. [Online]. Available: https://circabc.europa.eu/sd/d/62415be2-3d5a-4b3f-b29a-d1760f4dc11a/Lot11 Motors 1-8 final 28-04-08.pdf

[9] European Commission, "COMMISSION REGULATION (EU) 2019/1781," Brussels, Belgium, 2019. [Online]. Available: https://eur-lex.europa.eu/eli/reg/2019/1781/oj

[10] European Commission, "Stepping up Europe's 2030 climate ambition. Investing in a climate-neutral future for the benefit of our people." COM, 2020. Accessed: Jul. 09, 2024. [Online]. Available: https://eur-lex.europa.eu/legal-content/en/ALL/?uri=CELEX:52020DC0562

[11] NREL - National Renewable Energy Laboratory, "REMPD: Renewable Energy Materials Properties Database," Renewable Energy Materials Property Database. US Department of Energy (DOE). Accessed: Jul. 09, 2024. [Online]. Available: https://www.nrel.gov/wind/materials-database.html

[12] ENTSO-E - European Network of Transmission System Operators, "Power Statistics," Brussels, Belgium, Jun. 2024. Accessed: Jul. 09, 2024. [Online]. Available: https://www.entsoe.eu/data/power-stats/

[13] E. Commission, I. Directorate-General for Internal Market Entrepreneurship and SMEs, M. Grohol, and C. Veeh, *Study on the critical raw materials for the EU 2023 – Final report*. Publications Office of the European Union, 2023. doi: doi/10.2873/725585.

[14] B. Sprecher *et al.*, "Life Cycle Inventory of the Production of Rare Earths and the Subsequent Production of NdFeB Rare Earth Permanent Magnets," *Environ Sci Technol*, vol. 48, no. 7, pp. 3951–3958, Apr. 2014, doi: 10.1021/es404596q.

[15] B. Hassan, "Perspective Chapter: Environmental Impact of Modern Permanent Magnets," in *Modern Permanent Magnets*, D. R. Sahu, Ed., Rijeka: IntechOpen, 2023. doi: 10.5772/intechopen.111661.

[16] K. Binnemans *et al.*, “Recycling of rare earths: A critical review,” *J Clean Prod*, vol. 51, pp. 1–22, 2013, doi: 10.1016/j.jclepro.2012.12.037.

[17] T. Elwert, D. Goldmann, F. Roemer, and S. Schwarz, “Recycling of NdFeB Magnets from Electric Drive Motors of (Hybrid) Electric Vehicles,” *Journal of Sustainable Metallurgy*, vol. 3, no. 1, pp. 108–121, 2017, doi: 10.1007/s40831-016-0085-1.

[18] A. Rassõlkin *et al.*, “Life cycle analysis of electrical motor drive system based on electrical machine type,” *Proceedings of the Estonian Academy of Sciences*, vol. 69, no. 2, pp. 162–177, 2020, doi: 10.3176/proc.2020.2.07.

[19] R. Hernandez-Millan, J. R. Pacheco-Pimentel, and J. Salinas, “Design principles for recycling induction motors,” in *IEMDC 2001. IEEE International Electric Machines and Drives Conference (Cat. No.01EX485)*, 2001, pp. 782–788. doi: 10.1109/IEMDC.2001.939406.

[20] R. Hernández-Millán and J. R. Pacheco-Pimentel, “Recycling rotating electrical machines,” *Revista Facultad de Ingenieria*, vol. 2017, no. 83, pp. 50–56, 2017, doi: 10.17533/udea.redin.n83a07.