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Research Article

Recycling Potential in the European Union (EU) of Low Voltage Three-Phase Induction Motors Up to 75 kW of Power: Quantitative Analysis

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Abstract

This article quantifies the recycling potential of the metallic materials that make up three-phase induction motors. The data on the use of electric motors by type and power determines that the most significant recycling potential lies in this low-voltage motor which powers up to 75 kW. The work aims to show the possibility of such recycling in the European Union (EU). The metals used to make the various parts of the induction motor and the main recycling methods that allow their reuse are listed. It evaluates which part of the motor can apply these recycling methods relatively easily (stator) and which part is more complex (rotor). A calculation process is used to exhaustively quantify the metals that incorporate different motors selected for other powers to determine the amounts of material that can be recycled and reused to manufacture new equipment. The recycling potential is quantifies by parts (stator and rotor) employing approximate equations obtained from the study and by materials (copper, aluminum, magnetic sheet, steel). The data calculated, the economic volume, the possibilities of energy-saving, and the environmental advantages of dedicating efforts and resources for collecting, recycling, and reusing the materials in three-phase induction motors for industrial applications show. The withdrawal of electric motors in industrial applications, due to causes related to the restructuring of production processes, manufacturing systems, breakdowns, or directly due to aging, generates considerable possibilities of reusing the metals used in their manufacture.

Keywords

Induction motors; recycling; reuse; copper; aluminum; magnetic sheet

1. Introduction

Induction motors (IM) represent practically 90% of the total market share of low-voltage electric motors used (United for Efficiency, 2017; De Almeida et al., 2011) [1, 2], and the IM is the electric motors most currently used in industrial applications in different sectors:

- Pumps: 24.8%.
- Material processing: 22.5%.
- Compressed air: 15.8%.
- Fans: 13.7%.
- Material handling: 12.2%.
- Refrigeration: 6.7%.
- Others: 4.3%.

The motors stock is currently mainly installed in the minor powers range, withalmost 90% in powers up to 750 W, practically 10% between 0.75 kW to 375 kW, and only 0.03% in power greater than 375 kW [3].

The above data considers it convenient to focus the study of the potential and the possibilities of recycling electric motors for industrial applications into three-phase low-voltage induction motors [4]. We will quantify the recycling potential in the European Union (EU) case regarding the geographical scope.

The objective set in the work is to quantify the recycling potential of the metals that make up induction motors, such as copper, aluminum, and magnetic sheet metal [5, 6]. These metals make up the main parts of this type of motor. In addition, the behavior of these metals once recycled allows them to be reused several times and for long periods [7, 8].

The reuse of these metals after their recycling has a significant economic impact, especially in aspects related to the circular economy [9, 10].

Although the potential recycling of metals is known, the article addresses the subject of induction motors particularly and quantifies said potential through a methodology based on the real dimensions of the motors studied, establishing a calculation procedure that allows this potential to be numerically evaluated.

In this article, chapter 2.1 lists the metallic materials used to manufacture induction motors. Chapter 2.2 lists some of the recycling methods that can use for these metals. Chapter 3.1 quantifies the amount of metal used by the power range. Chapter 3.2 quantifies the recycling potential based on EU market data and construction data provided previously. Regulatory, economical, and environmental aspects appear in chapter 4, the conclusions derived from the work are listed.

2. Materials and Methods

2.1 Metals Used in the Manufacture of Induction Motors

Of the different materials necessary for the manufacture of induction motors, in the study carried out, we will focus only on the recycling potential of the primary metals used, representing approximately 98% of the total materials that a motor contains [11]. In Figure 1, the parts that make up the induction motors are indicated, where:

- stator cage: made of aluminum or cast iron.
- stator winding: copper wire or copper plate.
- stator core: ferromagnetic silicon iron sheet.
- rotor shaft: steel.
- rotor winding: aluminum squirrel cage (copper only in some high-efficiency motors). Copper wire is used in wound rotor motors.
- rotor core: ferromagnetic silicon iron sheet.

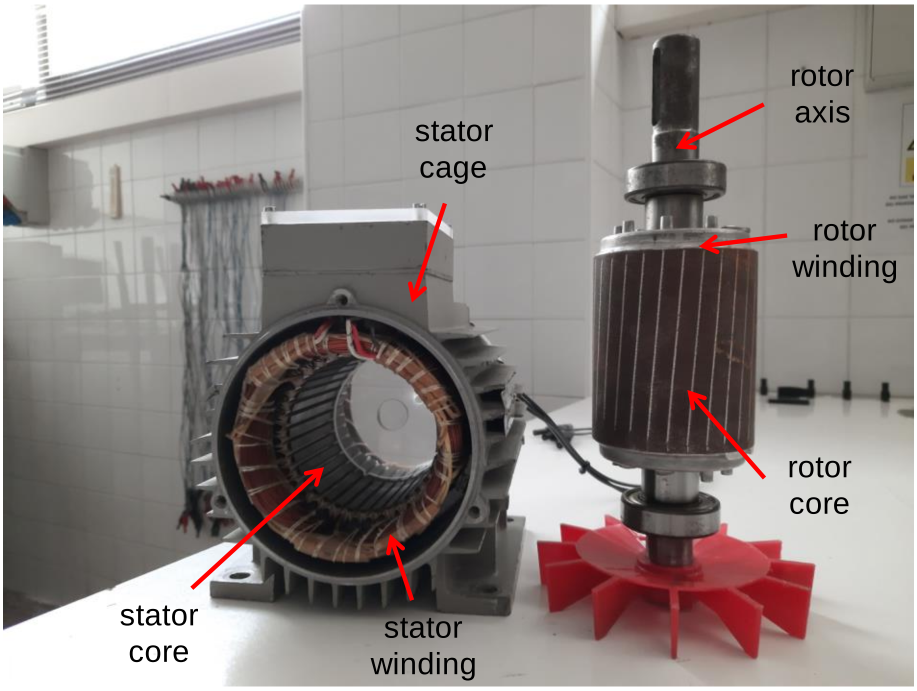


Figure 1 Main parts in a three-phase induction motor (photo of a 1.5 kW motor).

At the end of the motor's life cycle, metals such as copper, steel, and aluminum can be recycled almost entirely and many times. In the case of cores made of ferromagnetic material, since they are generally iron alloys with a silicon percentage of around 3%, it further complicates their recycling possibilities.

As the energy required for the reuse of metals from the scrapping of these motors is considerably less than the energy needed to obtain these from the sources (minerals and concentrates), it is of great interest both from the economic point of view and environmental recovery and reuse of these metals [12].

2.2 Metal Recycling Methods Applicable to Induction Motors

Effective recycling will depend on the high-quality separation of the material fractions that can be achieved, and it is sometimes necessary to apply a combination of different techniques. The methods used for recycling electrical machines are disassembling and shredding [13].

2.2.1 Motor Disassembly

The metals that make up the motor's stator are separated relatively quickly using specific machinery, Figure 2. Generally, the outer parts and accessories can be removed and put aside (2a). The outer casing is separated and extracted by pressure exerted by a dividing apparatus. The aluminum or cast iron casing is cut on the opposite sides to be separated from the stator core (2b). Subsequently, the nucleus splits into two equal pieces (2c). When opened, the copper coils are exposed and ready for separation. A hydraulic system removes the copper wiring from the ferromagnetic core. The machine's teeth grab the winding and the rods, and the hydraulic drive pushes the housing, leaving the copper wiring exposed and loose (2d).

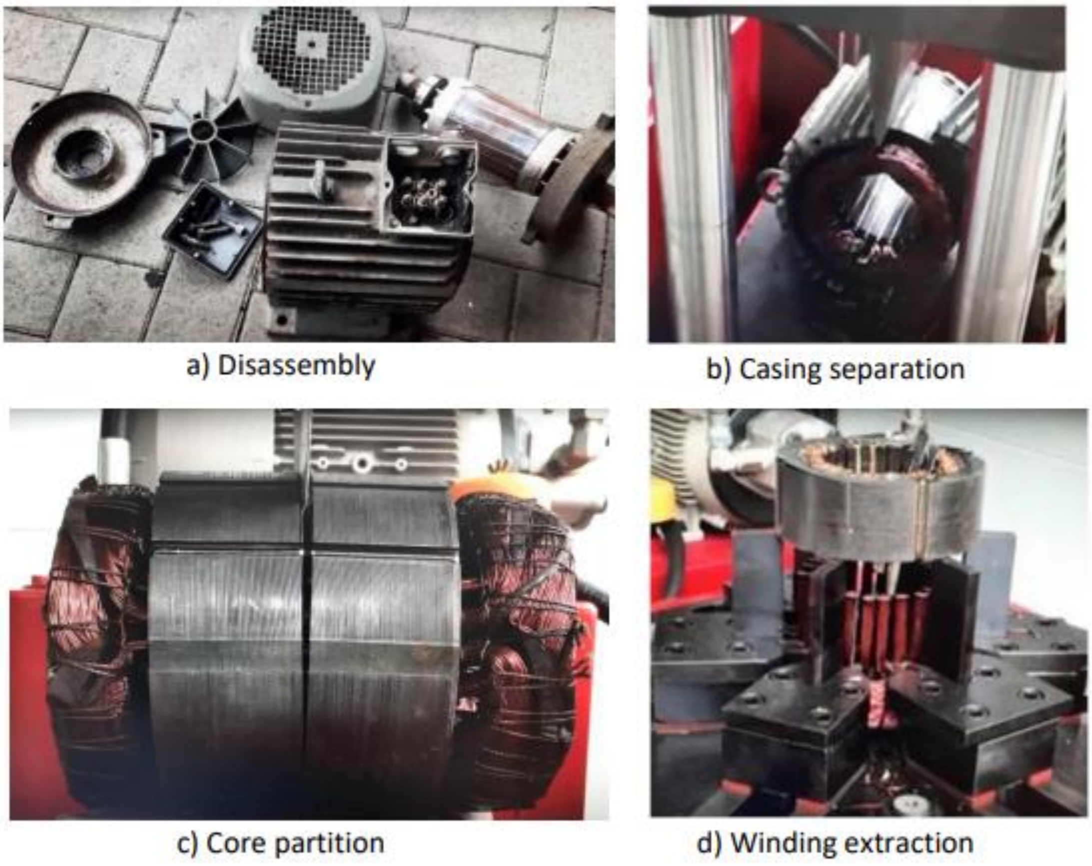


Figure 2 The disassembly process of the stator of the motor for metal recycling. (courtesy of Bronneberg, recycling machines and services, https://www.bronneberg.es) [14].

After disassembling the different parts, sometimes some can be reused directly, although, in the case of metals, they generally have to be re-melted as the same raw material.

In the rotor case, if the motor is a wound rotor, proceed as in the stator. For motors with the squirrel cage winding, used chiefly, recycling is much more complex due to the injection of aluminum into the ferromagnetic core grooves. The currently used procedure consists of separating the shaft by pressure, then wholly crushing the ferromagnetic core with the squirrel cage's aluminum winding to proceed to its separation [15].

2.2.2 Shredded

In the shredded process, metals are crushed into small pieces by manual or automated procedures, particularly in determining the ground particles' appropriate size, requiring an exemplary grinding corresponding to a particle size between 1 and 2 mm. This procedure can be achieved using cutting mills and a preliminary cryogenic treatment that cools the materials with liquid hydrogen.

2.2.3 Separation

The separation of the different materials is done by gravity or by magnetic methods. By gravity, it is carried out by applying an airflow that separates the particles according to their density or by sinking/floating systems. Using permanent magnets or eddy current devices, ferromagnetic materials are separated from the rest by magnetic methods.

2.2.4 Treatment of Separated Metals

The most common treatments are listed below, depending on the type of metal.

<u>Ferromagnetic Iron Sheet and Steel of Rotor Shaft</u>. Iron and steel are recycled through selective oxidation [16]. Impurities are oxidized at 1600°C and then removed as gas or foam. This method does not remove all impurities, but Silicon, the usual impurity in magnetic sheets, can remove without problems. Once the impurities are eliminated, the iron and steel smelts. In shafts, mainly carbon steel is used and can also remove carbon impurities without oxidation problems.

<u>Copper</u>. Like iron and steel, copper is recycled through oxidation to remove impurities [17]. The refining process is carried out by electrolysis. It can enhance this refining electrolysis by combining a copper sulfate electrolyte of sulfuric acid that provides copper with a purity of 99.98%. Another possibility of recycling copper is through hydrometallurgy, although this process is more applicable for electronic equipment with low copper content and mixed with other materials.

<u>Aluminum</u>. When refining aluminum, separating cast and forged alloys is essential to ensure efficient cleaning (Capuzzini et al., 2018) [18]. Melting occurs typically at temperatures between 700°C and 900°C. In very pure aluminum fractions of generated materials, it is recycled through so-called recasts. On the contrary, molten alloys with many impurities must be processed by refining, and adding fusion salts must facilitate the melting processes.

3. Results

3.1 Raw Materials in Induction Motors

To quantify the recycling potential in induction motors, the objective of the work carried out, a calculation procedure has been developed for the motor's design and dimensioning that allows the exact amounts of each metal that make it up to be determined. Due to the variety of construction types, efficiency classes, etc., that currently exist on the market and that contrast the amounts of material to be used in each case, it has been necessary to establish common hypotheses to limit the study's development. The established premises are:

- Low voltage three-phase motors (less than 1000 V).
- Motors with 2 or 4 poles and frequency 50 Hz.
- Motors with aluminum casing and squirrel cage rotors are also made of aluminum.
- Motors of efficiency class IE2.

Regarding the powers concerned, the study has been limited to 75 kW because they cover a very high percentage of units installed in the industry. Furthermore, it is manufactured mainly with enameled copper conductors in the stator up to this power. The machines currently used for recycling the stators can treat motor casing diameters up to this power.

Appendix A shows the primary nominal data of the motors selected in this study, and Table 1 shows the main geometric dimensions of these motors (Boldea et al., 2002) [19].

Table 1 Main dimensions of induction motors.

Output Power (kW)	Outer diameter of the stator (mm)	Outer diameter of the rotor (mm)	Axial length (mm)	stator/rotor slots	Number of conductors per slot (stator)
0.04	60	30	45	12/15	620
0.25	100.5	55	58	24/17	230
0.75	124.7	70.5	60	30/22	78
1.5	150	88.4	100	36/28	56
5.5	205	115	110	36/28	28
7.5	212	119	125	24/20	48
15	250	150	200	48/44	20
22	290	160	230	48/40	11
30	320	190	250	60/48	12
45	335	220	260	48/38	12
75	400	260	280	48/40	9

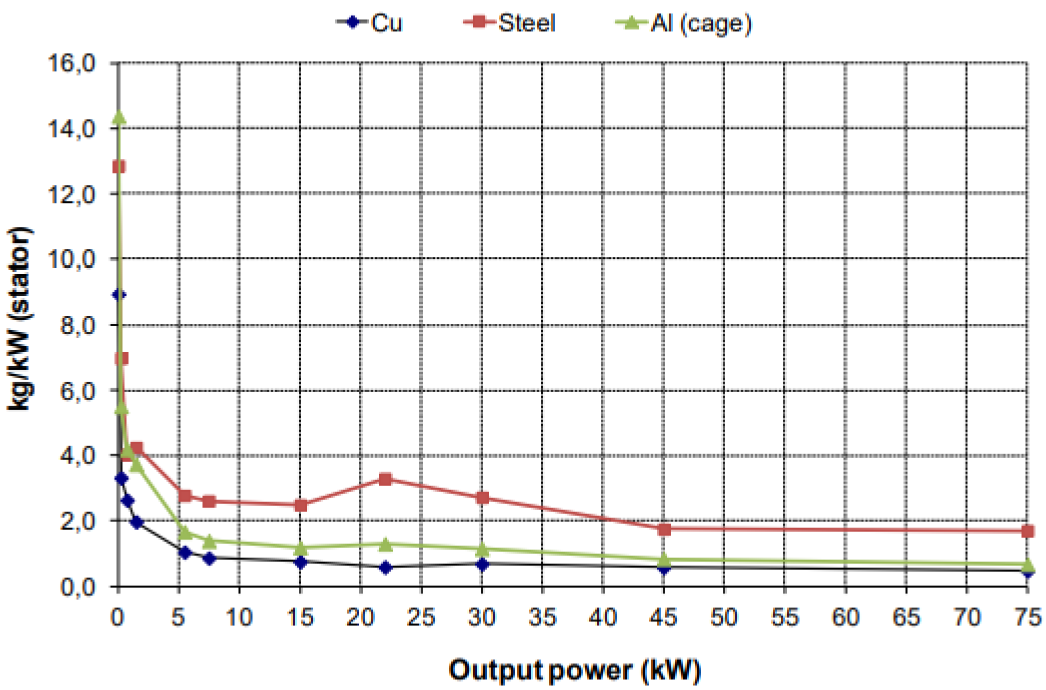
With the nominal data and the main dimensions, a calculation and sizing procedure has been developed to determine the quantities of metals necessary for the motors' manufacture. Table 2 shows the results obtained, where the separation between stator and rotor has been made (Pyrhönen et al., 2008; Cathey, 2000; Hamdi, 1994; Parasiliti et al., 2013) [20-23]. The calculation procedure to obtain the quantities of metals with recycling potential in each motor are shown in Appendix C.

Table 2 Raw metals of induction motors (in kg).

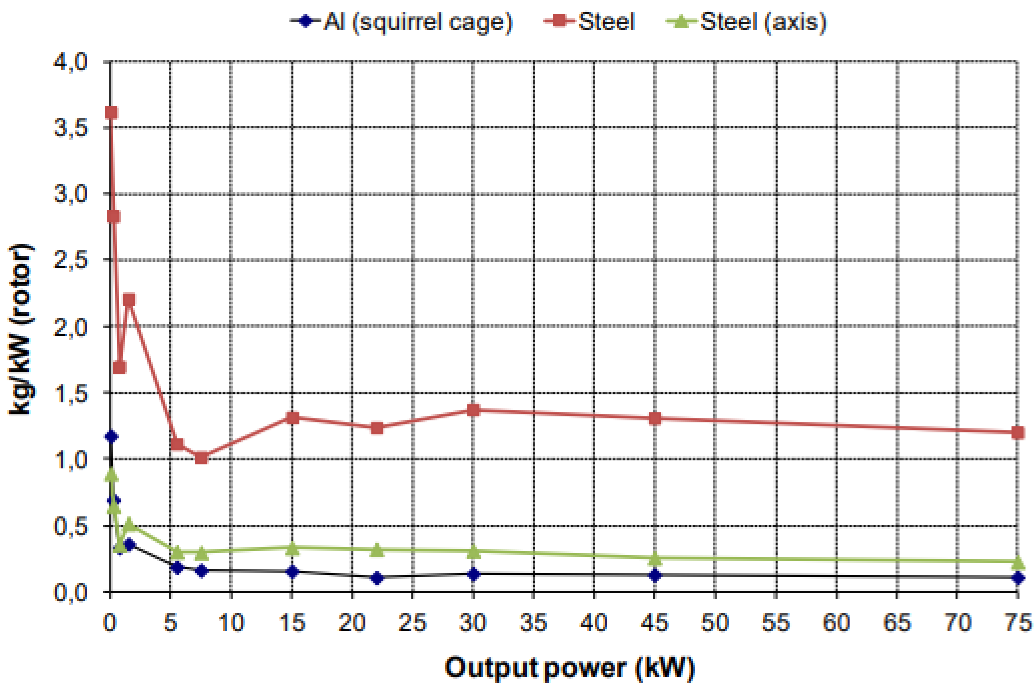
	Stator			Rotor		
Output Power (kW)	Copper (conductors)	Steel (core)	Aluminium (cage)	Aluminium (squirrel cage)	Steel (core)	Steel (axis)
0.04	0.358	0.514	0.575	0.047	0.145	0.036
0.25	0.83	1.746	1.377	0.172	0.708	0.161
0.75	1.976	3.028	3.147	0.25	1.271	0.267
1.5	2.957	6.379	5.598	0.541	3.311	0.772
5.5	5.722	15.292	9.163	1.026	6.115	1.664
7.5	6.449	19.587	10.397	1.219	7.593	2.229
15	11.202	37.357	17.77	2.337	19.677	5.01
22	12.842	72.534	28.507	2.353	27.176	7.099
30	20.387	81.69	34.394	4.079	41.141	9.337
45	25.712	78.648	37.544	5.77	58.782	11.556
75	35.046	127.666	49.974	8.203	89.89	16.939

The design of new electric motors, considering the aspects of their recycling at the end of their life cycle, is a very interesting topic. However, it's not addressed in this article [24].

From Table 2, the metals used have been quantified using the weight/power ratio (kg/kW) for stator and rotor separately, Figure 3. For the study's prospective recycling potential objective, three categories have been differentiated according to the motor power: small power up to 0.75 kW, medium power between 0.75 kW-7.5 kW, and high power between 7.5 kW-75 kW. This classification will allow us to use the market data presented in the next section. The ratios obtained in the three established categories allow a better mathematical approximation, as Appendix B shows.



a) Stator



b) Rotor

Figure 3 Ratios weight/power (kg/kW) for the different metals.

3.2 Assessment of Recycling Potential in the European Union (EU)

In 2011, the world stock of electric motors installed for industrial applications was approximately 2 billion units below 0.75 kW, 230 million in powers between 0.75 kW-375 kW, and 0.6 million in powers above 375 kW. As far as the European Union (EU) is concerned, in this section, the data indicated in the document [25] have been used, which are data based on the statistical classification of economic activity in the European Union (provided by https://ec.europa.eu/eurostat/web/prodcom) [26]. The PRODCOM statistics aim to provide a complete EU-level picture of industrial production evolution for a given product or the industry.

According to CEMEP (https://cemep.eu/) [27], in 2010, the number of units of three-phase induction motors sold and the turnover was:

- 7,300,000 units (€580 million) in powers were lower than 0.75 kW.
- 8,100,000 units (€2,700 million), in powers between 0.75 kW-375 kW.
- 135,000 units (€340 million), in powers greater than 375 kW.

In a more specific power classification, extended to all polyphase alternating current motors (excluding traction motors), according to PRODCOM:

- 11,700,000 units (53.42% of the total), in powers lower than 0.75 kW.
- 8,366,000 units (38.2% of the total), in powers between 0.75 kW-7.5 kW.
- 1,512,000 units (6.9% of the total), in powers between 7.5 kW-37 kW.
- 202,000 units (0.92% of the total), in powers between 37 kW-75 kW.
- 94,000 units (0.43% of the total), in powers between 75 kW-375 kW.
- 21,000 units (0.1% of the total), in powers between 375 kW-750 kW.
- 7,000 units (0.03% of the total), in powers greater than 750 kW.

The estimate made in 2010 on the stock of installed motors, based on the number of motors sold annually, the estimated life span, and the growth rate established in the EU, provides the following data:

- 77,355,000 units, in powers lower than 0.75 kW.
- 92,852,000 units, in powers between 0.75 kW-375 kW.
- No data in powers higher than 375 kW.

The sales market trend for three-phase induction motors in the EU has remained relatively stable in recent years, so it is estimated that the data presented above will tend to vary significantly little in the short term. In some cases, such as in powers lower than 0.75 kW, the market may increase its presence in replacing single-phase induction motors due to the introduction of variable-speed drives. However, the power supply is single-phase, the inverter + three-phase motor set will replace the single-phase motor. Also, the number of motors can increase at high powers due to traction motors in electric mobility. In this case, the three-phase induction motor will compete with other motors that seem better positioned for this application, such as the Brushless or synchronous motor with permanent magnets.

For the prospective recycling potential, using the stock and sales data presented above has been considered, establishing an average annual market growth of 2.1%, equivalent to the increase in electricity consumption in the EU in recent years.

Considering [25]:

- An estimated life span of 10 years for small power motors, 12 years for medium power motors, and 15 years for high power motors.
- An annual sales growth rate of 2.1%.
- Annual removal of motors obtained from equation (1):

$$\mathrm{MR} = \frac{\mathrm{SMA} + \mathrm{MVA} - \mathrm{MRA}}{\mathrm{T}} \quad (1)$$

Where:
MR = number of motors retired per year in the new period to be considered.
SMA = stock of motors installed.
MVA = number of motors sold per year considering the annual growth rate.
MRA = number of motors removed annually corresponding to the previous installation period.
T = estimated years of motor life.

For all the above, from (1), the forecast of the number of motors to be removed in the 2021-2030 period is obtained by the power range considered, forecast shown in Figure 4.

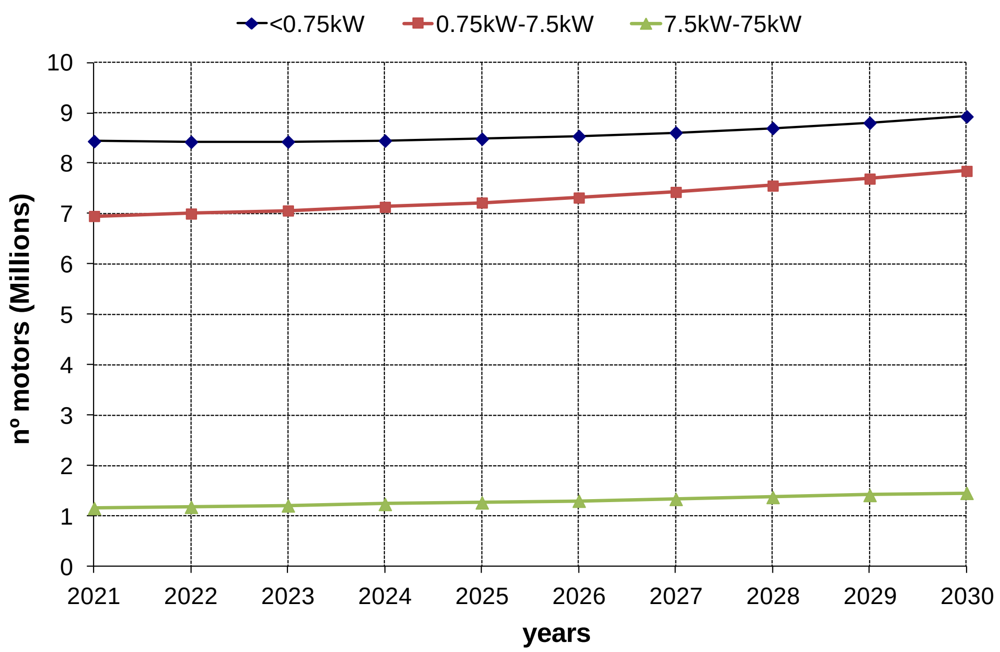


Figure 4 Forecast of the number of motors to retire (in millions of units) in the period 2021-2030 by power range.

Based on the distribution of sales by powers in each category (provided by https://ec.europa.eu/eurostat/web/prodcom) [26], an estimate of the percentage of sales has been made for each of the standardized powers that manufacturers offer in their catalogs, obtaining the distributions for each standard category, in%, indicated in Figure 5.

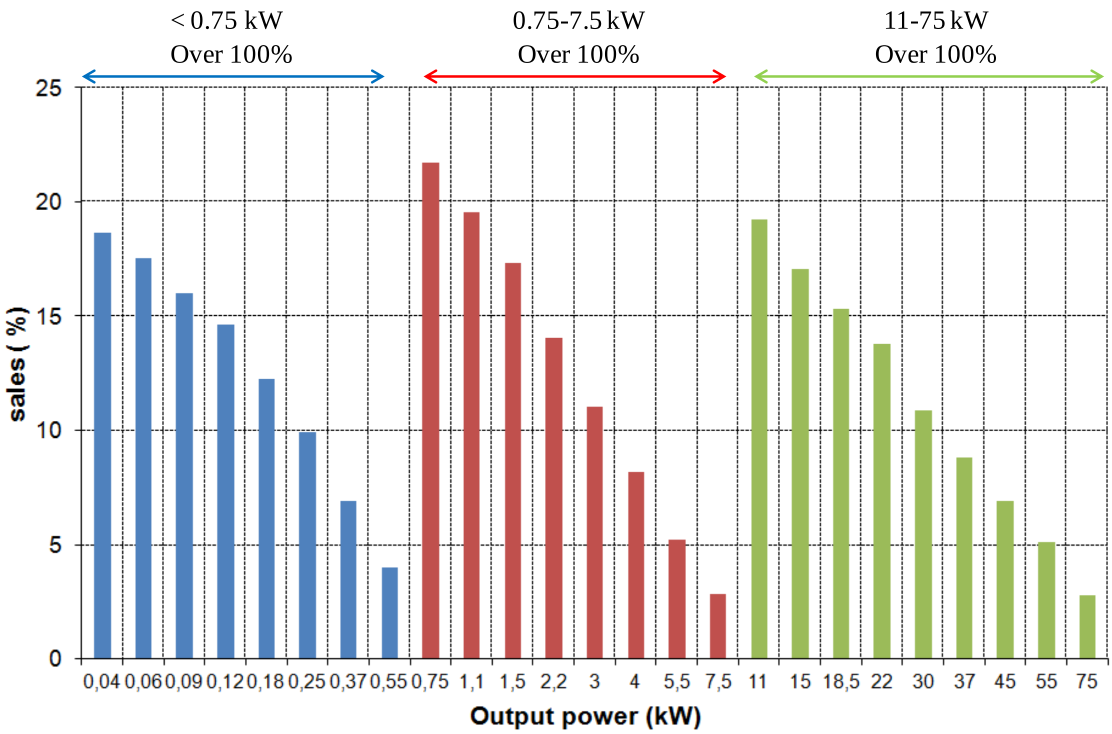
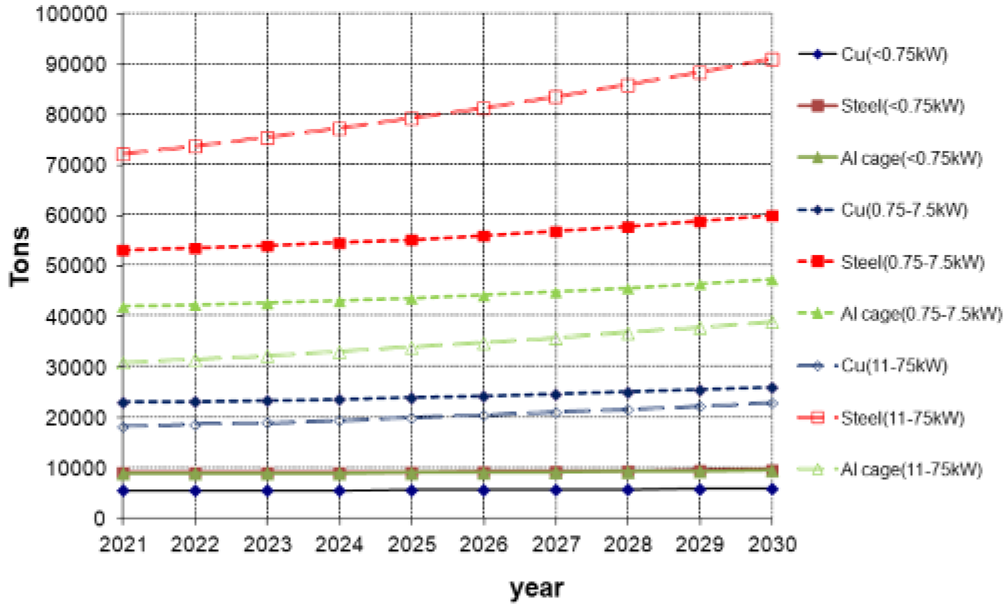
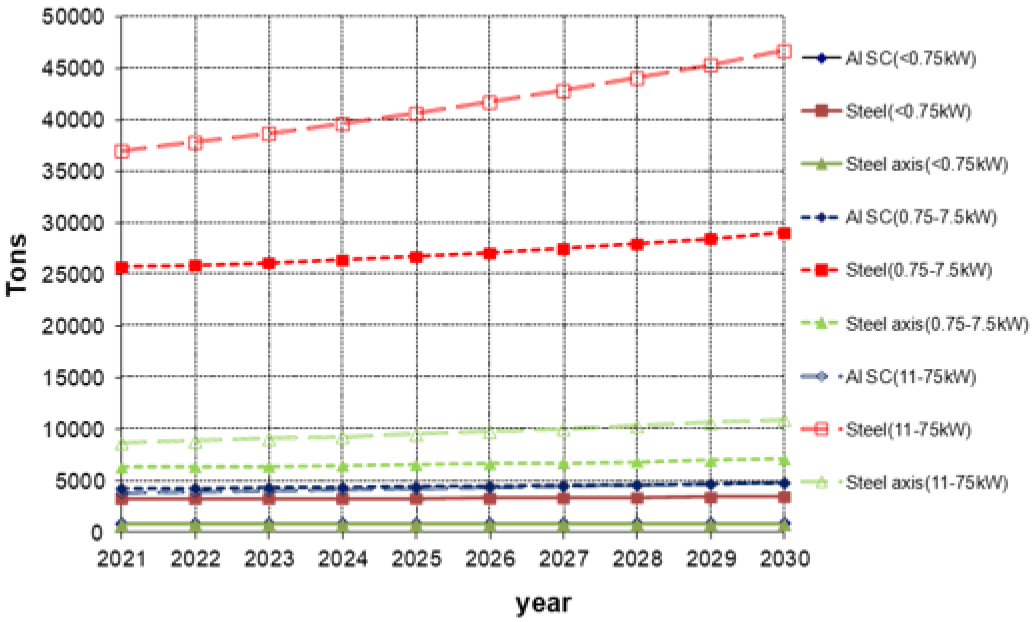


Figure 5 Percentage of sales forecast (by power standard categories).

The number of motors to be removed is obtained for each normalized power by applying the above percentages to the forecast shown in Figure 5. Next, using equation (B.1) and the coefficients in Table B.1, metals' potential to be recycled by motor power and category has been calculated. Figure 6 shows the final results obtained for metals' expected potential to be recycled for 2021-2030, differentiated by power category and by motor parts.



a) Stator



b) Rotor

Figure 6 Forecast of the potential of metals to be recycled in the period 2021-2030.

4. Regulatory, Economical, and Environmental Aspects

Although it is not the objective of this work to develop these aspects, we consider it appropriate to give a few notes on the general context to take into account due to their breadth and complexity [28]. However, considering that the total quantities potentially to be recycled that have been obtained in the study carried out are (estimate for the year 2021):

- 46,620 tons of copper.
- 90,513 tons of aluminum.
- 200,350 tons of magnetic sheet.

- 15,637 tons of steel.

4.1 Regulatory Aspects

It is essential to encourage recycling in general and the metals that make up electric motors, particularly the development of specific regulations that motivate and regulate their activity. In the EU, the existing basic reference regulation appears in (https://eur-lex.europa.eu/) [29]:

- Directive 2008/98/EC on waste.
- Directive 2012/19/EU on waste electrical and electronic equipment (WEEE).
- European standard EN 45555/2019: General methods for assessing the recyclability and recoverability of energy-related products.
- European standard EN 45557/2020: General method for assessing the proportion of recycled material content in energy-related products.

4.2 Economical Aspects

As a guide, the cost of the metals used in the manufacture of electric motors has been estimated at approximately [30, 31]:

- 5.5 €/kg for copper.
- 1.7 €/kg for aluminum.
- 2.3 €/kg for the magnetic sheet.
- 0.57 €/kg for steel.

From the potential to recycle obtained, the economic quantities can handle annually by the recycling industry would amount to (for the year 2021):

- 256.41 M € with copper.
- 153.87 M € with aluminum.
- 460.8 M € with the magnetic sheet.
- 8.91 M € with steel.

These amounts give us an idea of the electric motor recycling industry's economic volume (around 880 million euros annually). In addition to companies, employment, etc., derived from the activities necessary for this recycling to be effective, from collecting the metals to developing specific machinery for their separation and treatment.

4.3 Environmental Aspects

The environmental benefits of metal recycling derive mainly from the savings in the energy consumption necessary to produce the same amount of metal from material from recycling concerning the original raw material from mining extractions. As a guide, it has been established that this energy saving in the metals that make up electric motors can be approximated:

- 80/85% for copper.
- 90/95% for aluminum.
- 70/75% for steel.

Also, as in the aluminum case, the more times it is recycled, the need for energy for its subsequent treatment to be reused decreases.

According to the publication presented by the Bureau of International Recycling [32], obtaining metals from recycling to primary extraction, is estimated that, approximately, can quantify the savings in:

- Copper: 10.6 MJ/kg in energy savings and 0.81 tCO_2/t in equivalent CO_2 emissions.
- Aluminum: 44.6 MJ/kg in energy savings and 3.54 tCO_2/t in equivalent CO_2 emissions.
- Steel: 2.3 MJ/kg in energy savings and 0.97 tCO_2/t in equivalent CO_2 emissions.

Therefore, the savings potential that can obtain amounts to annually (for the year 2021):

- Copper: 494.18 MJ in energy savings and 207.69 tCO_2 in equivalent CO_2 emissions.
- Aluminum: 4036.9 MJ in energy savings and 544.71 tCO_2 in equivalent CO_2 emissions.
- Magnetic sheet: 460.8 MJ in energy savings and 446.98 tCO_2 in equivalent CO_2 emissions.
- Steel: 35.96 MJ in energy savings and 8.64 tCO_2 in equivalent CO_2 emissions.

Thus, annually energy can save by about 5027.86 MJ and reduce equivalent CO_2 emissions by about 1208.03 tCO_2. Environmental impact assessment applied to electric motors can be carried out by life cycle analysis [33] using the MEErP methodology [34].

5. Conclusions

The potential for metal recycling in electric motors in general and in three-phase induction motors, in particular, is clear. This article has quantified this potential within the European Union (EU) framework, limiting the study to low voltage motors and for powers up to 75 kW.

Although the amounts of material used to manufacture three-phase induction motors may vary according to their characteristics, depending on the voltage, the number of poles, performance class, etc., a calculation methodology has been established. This methodology allows quantifying the weights of copper, aluminum, magnetic sheet, and steel for the different standard powers that appear in the manufacturers' catalogs.

The volume of sales in the EU has also been estimated from the available data provided by market studies, which has made it possible to quantify the needs in industrial applications of these motors and to carry out a perspective for the next decade.

The metals that make up the stator of three-phase induction motors can be carried out relatively easily from specific machinery already available on the market. These metals can be reused with the consequent energy savings and the environmental benefits of this reuse.

More complex is recycling the rotor metals due to the difficulty of separating the squirrel cage winding from the ferromagnetic core. Even so, utilizing specific machinery for their crushing and subsequent separation of components, the potential quantified in this work predicts that the necessary investments in recycling three-phase induction motors have an excellent short-term present and future.

Besides a rigorous market analysis, a methodology based on the real dimensions of the induction motors is presented. Together, these two aspects, permit a calculation procedure that allows the recycling potential in these motors to be numerically evaluated.

Author Contributions

The author did all the research work of this study.

Competing Interests

The author has declared that no competing interests exist.

Additional Materials

The following additional materials are uploaded at the page of this paper.

1. Appendix A: Table S1 shows the nominal data of the motors selected in the study developed.
2. Appendix B: By power motors category, differentiating between stator and rotor and by the metal used, the weight/power ratios have been approximated to a potential equation (B.1).
3. Appendix C: This Appendix shows, in a simplified way, the procedure for calculating the quantities of metals in the different motors studied.

References

1. De Almeida AT, Ferreira FJ, Fong JA. Standards for efficiency of electric motors. IEEE Ind Appl Mag. 2010; 17: 12-19.
2. United for efficiency (U4E). Accelerating the global adoption of energy-efficient electric motors and motor systems. Paris: UN environment-global environment facility; 2017.
3. Market analysis report. Electric motor sales market size, share & trends analysis report by application, by power output (integral HP output, fractional HP output), by motor type (hermetic, AC, DC), by region, and segment forecasts, 2021-2028. San Francisco: Grand View Research, Inc.; 2021.
4. de Almeida AT, Ferreira FJ, Fong J. Perspectives on electric motor market transformation for a net zero carbon economy. Energies. 2023; 16: 1248.
5. André H, Ljunggren M. Short and long-term mineral resource scarcity impacts for a car manufacturer: The case of electric traction motors. J Clean Prod. 2022; 361: 132140.
6. Stratiotou Efstratiadis V, Michailidis N. Sustainable recovery, recycle of critical metals and rare earth elements from waste electric and electronic equipment (circuits, solar, wind) and their reusability in additive manufacturing applications: A review. Metals. 2022; 12: 794.
7. Charpentier Poncelet A, Helbig C, Loubet P, Beylot A, Muller S, Villeneuve J, et al. Losses and lifetimes of metals in the economy. Nat Sustain. 2022; 5: 717-726.
8. Watari T, Nansai K, Nakajima K. Review of critical metal dynamics to 2050 for 48 elements. Resour Conserv Recycl. 2020; 155: 104669.
9. Li Z, Che S, Wang P, Du S, Zhao Y, Sun H, et al. Implementation and analysis of remanufacturing large-scale asynchronous motor to permanent magnet motor under circular economy conditions. J Clean Prod. 2021; 294: 126233.
10. Tiwari D, Miscandlon J, Tiwari A, Jewell GW. A review of circular economy research for electric motors and the role of industry 4.0 technologies. Sustainability. 2021; 13: 9668.
11. De Almeida AT, Ferreira F, Fong J, Fonseca P. Eup lot 11 motors. Technical study for ecodesign directive. Coimbra Portugal: European Commission; 2008.
12. Torrent M, Martínez E, Andrada P. Life cycle analysis on the design of induction motors. Int J Life Cycle Assess. 2011; 16: 1. doi: 10.1007/s11367-011-0332-4.

13. Link R. Innovative approaches to recycling of small and electric motors from end-of-life vehicles, electric bicycles and industrial machinery. Stockholm: Royal Institute of Technology; 2016.
14. Recycling machines and services [Internet]. Madrid: Bronneberg; [cited date 2022 April 16]. Available from: https://www.bronneberg.es.
15. Salama A, Richard G, Medles K, Zeghloul T, Dascalescu L. Distinct recovery of copper and aluminum from waste electric wires using a roll-type electrostatic separator. Waste Manage. 2018; 76: 207-216.
16. Branca TA, Colla V, Algermissen D, Granbom H, Martini U, Morillon A, et al. Reuse and recycling of by-products in the steel sector: Recent achievements paving the way to circular economy and industrial symbiosis in Europe. Metals. 2020; 10: 345.
17. Loibl A, Espinoza LAT. Current challenges in copper recycling: Aligning insights from material flow analysis with technological research developments and industry issues in Europe and North America. Resour Conserv Recycl. 2021; 169: 105462.
18. Capuzzi S, Timelli G. Preparation and melting of scrap in aluminum recycling: A review. Metals. 2018; 8: 249.
19. Boldea I. Induction machines handbook. New York: CRC press; 2020.
20. Cathey JJ. Electric machines: Analysis and design applying mathlab. McGraw-Hil; 2001.
21. Hamdi ES. Design of small electrical machines. Hoboken, New Jersey, United States: John Wiley & Sons, Inc.; 1994.
22. Parasiliti F, Villani M. IE3 induction motor design with aluminum and copper rotor cage: A comparison. Proceedings of the 8th International Conference EEMODS'2013 Energy Efficiency in Motor Driven Systems; 2013 October 28-30; Rio de Janeiro, Brazil.
23. Pyrhönen J, Jokinen T, Hrabovcova V. Design of rotating electrical machines. Hoboken, New Jersey, United States: John Wiley & Sons, Ltd.; 2008. ISBN: 978-0-470-69516-6.
24. Alatalo M, Lundmark ST, Grunditz EA. Electric machine design for traction applications considering recycling aspects-review and new solution. Proceedings of IECON 2011-37th Annual Conference of the IEEE Industrial Electronics Society; 2011 November 07-10; Melbourne, Victoria, Australia. Piscataway, New Jersey, United States: IEEE.
25. De Almeida A, Falkner H, Fong J, Jugdoyal K. Eup lot 30: Electric motors and drives. Coimbra, Portugal: University of Coimbra; 2014.
26. Prodcom-Statistics by products-Overview [Internet]. Luxembourg: Eurostat; [cited date 2022 March 30]. Available from: https://ec.europa.eu/eurostat/web/prodcom.
27. European Committee of Manufacturers of Electrical Machines and Power Electronics [Internet]. [cited date 2022 March 30]. Available from: https://cemep.eu.
28. Hischier R, Böni HW. Combining environmental and economic factors to evaluate the reuse of electrical and electronic equipment–a Swiss case study. Resour Conserv Recycl. 2021; 166: 105307.
29. Access to European Union law [Internet]. [cited date 2022 April 12]. Available from: https://eur-lex.europa.eu.
30. Jardot D, Eichhammer W, Fleiter T. Effects of economies of scale and experience on the costs of energy-efficient technologies-case study of electric motors in Germany. Energy Effic. 2010; 3: 331-346.
31. Rassõlkin A, Kallaste A, Orlova S, Gevorkov L, Vaimann T, Belahcen A. Re-use and recycling of different electrical machines. Latv J Phys Tech Sci. 2018; 55: 13-23.

32. Bureau of international recycling (BIR). Report on the environmental benefits of recycling. BIR; 2016.
33. Torrent M, Martinez E, Andrada P. Assessing the environmental impact of induction motors using manufacturer's data and life cycle analysis. IET Electr Power Appl. 2012; 6: 473-483.
34. Methodology for ecodesign of energy-related products. Methodology report-Part 2: Environmental policies & data. Brussels/Delft: COWI Belgium sprl/VHK; 2011.