Comparative life cycle assessment of induction machines made with copper-cage or aluminium-cage rotors

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Comparative Life Cycle Assessment of Induction Machines made with Copper-cage or Aluminium-cage Rotors

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Abstract: This paper deals with Life Cycle Assessment (LCA) of induction machines and try to determine whether a copper-cage rotor is better than an aluminium-cage one, for a given using time and considering the global environmental footprint. The paper focuses on induction motors directly connected to the power grid, without electronic converters. The LCA takes into account the materials extraction, the machine construction, the use and the end of life for several criteria. In the first part, a copper conductor is compared to an aluminium one and results are discussed considering the part of recycled material in the rotor manufacturing process. In a second part, two machines with the same efficiency are compared. The environmental impacts differences are discussed. In the third part, two machines of the same sizes, but with a different rotor, are compared considering various usage times. The lower losses of the copper-rotor machine yield a significant advantage for the efficiency but the gains are smaller when the global life cycle is considered.

1. Introduction

In many countries, most of new industrial projects are developed considering their global environmental footprint. In ground transport systems for instance, the electrical motors reduce strongly the gas and particles emissions in towns. In aviation industry, aircrafts are designed with more efficient electric systems [1]. Therefore, many industrial sectors need compact and efficient motors.

Generally speaking, the permanent magnet synchronous motors yield the best performances [2]. However, magnet manufacturing has a high environmental cost. Variable reluctance machines provide also good performances without any magnet; their environmental cost is lower. These two technologies implement the principle of synchronous machines; they require a control by a suitable electronic converter, which is out of the scope to the paper. Conversely, induction machines (IM) are simpler [3]; they can be directly connected to the power grid and used for many industrial and domestic applications [4]. Most of Induction Machines are made with aluminium-cage rotors but it is possible to build more efficient Induction Machines with copper-cage rotors.

Several studies have shown the advantages of copper rotors to reduce joules losses [5] [6] [7] [8] [9]. However, the manufacture of copper-cage rotors has a higher environmental impact than standard aluminium-cage ones. Several Life Cycle Analysis (LCA) studies have shown that the additional environmental manufacturing cost of a better motor can be quickly compensated during the use phase [10] [11] [12] [13], but these studies concern general techniques of performance improvement. For example a bigger machine working at a lower flux density can be designed. It is also possible to use better magnetic sheets or bigger conductors working at a lower current density or better bearings. Few studies concerned complete LCAs of machines equipped with copper rotor [14]. This paper presents a comparison of the global environmental footprint between the aluminium and copper technologies, considering many criteria, in order to provide useful design tools based on a life Cycle Analysis.

2. Life Cycle Assessment

The Life Cycle Assessment (LCA) deals with environmental impacts of products, from raw materials extractions to end of life. All materials and energy consumed are evaluated, as well as wastes. For each environmental criterion, some rules are defined to obtain an environmental impact expressed with a representative unit. For example, the greenhouse gas emissions are expressed in an equivalent quantity of CO2. A lot of environmental criteria exist. In this study we chose 8 criteria inspired by the CML method developed by the Leiden University [15]. We include also additional criteria: IPCC (Intergovernmental Panel on Climate Change), cumulative energy, and ionizing radiation [16]; [17]. The table 1 of the appendix defines the considered criteria. The impacts of electricity depend on its origin. European electricity is considered for the motor construction. Concerning the motor use, both French and European electricity are retained (environmental impacts can be significantly different if the origin of electricity is different).

As it not possible to measure all the impacts, a life cycle analysis needs to use a generic database. ECOINVENT is the best known [18], it contains more than one million of products and processes. We used it with the software SIMAPRO.

The results can't be perfectly accurate because knowledge of environmental impacts is constantly evolving (as databases). Used materials and processes in LCA are generic and can't take everything into account. So the results have to be used as relative values allowing the comparison of the two rotor technologies for each criterion. Some criteria may be considered as more important than others depending on the application, but we have not classified them.

3. Environmental comparison of copper and aluminium

An easy way to compare the two conductive materials, (copper and aluminium) is to take two conductors with the same length and the same resistance; the only difference is the section. With the same resistance, the use phase of the two conductors is the same, only the impacts of their manufacturing and end of life must be taken into account.

The resistivity of the copper is $\rho_{Cu}=1.724\ 10^{-8}\Omega m$ at 300°K while this of aluminium is $\rho_{Al}=2.826\ 10^{-8}\Omega m$. So for the same resistance, the section of the aluminium conductor has to be multiplied by 1.639.

The density of the copper is $d_{Cu}=8.35$ while this of the aluminium is $d_{Al}=2.548$. Consequently for the same section, the mass of the copper conductor is 3.27 times more important.

The well-known equation (1) gives the resistance R in relation to the resistivity ρ, the length l and the section S,

$$R = \rho \frac{l}{S}. \qquad (1)$$

It can be deduced that, for the same resistance, the mass of a copper conductor is twice higher than that of an aluminium conductor despite a 60% lower volume.

Aluminium or copper may be primary, from mining and ore processing or secondary from recycling. For the transformation process, we choose in both cases a standard process of sheet rolling. For the end of life, we consider a recycling rate of 80% and consequently only 20% end up in landfill.

The figure 1 compares the environmental impacts of two conductors by considering primary resources, while figure 2 considers 50% of primary and 50% of secondary metals.

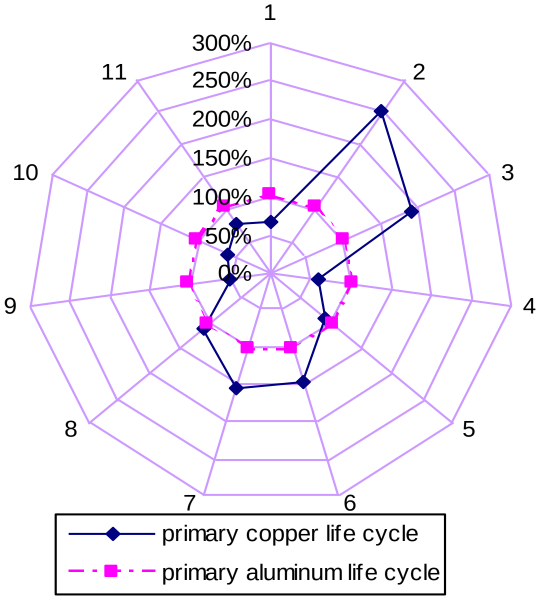

Fig. 1. Environmental impacts of copper or aluminium conductors from primary resources.

It can be observed in figure 1 than, for primary copper and aluminium, a little advantage is for copper which impact is less important for 6 among 11 criteria but worse for 5 others criteria. In details, lamination and end of life are less impacting for aluminium than for copper, but mining and ore processing are more impacting for aluminium, which explain the results. Consequently the situation is different if secondary metals are used. The influence of mining and ore processing are less important, and aluminium becomes better as shown in figure 2.

To conclude for the same resistance, aluminium is better than copper if it consists of at least 50% recycled material.

In all the cases, recycled metals are better than primary ones. For conductors, electrical machines manufacturers generally use primary metals to obtain the best IACS (International Annealed Copper Standard) conductivity. Nevertheless new technologies allow the use of secondary metals without any decrease of the conductivity. Cable manufacturers like Nexans indicate that 40% of their production is based on recycled copper for example.

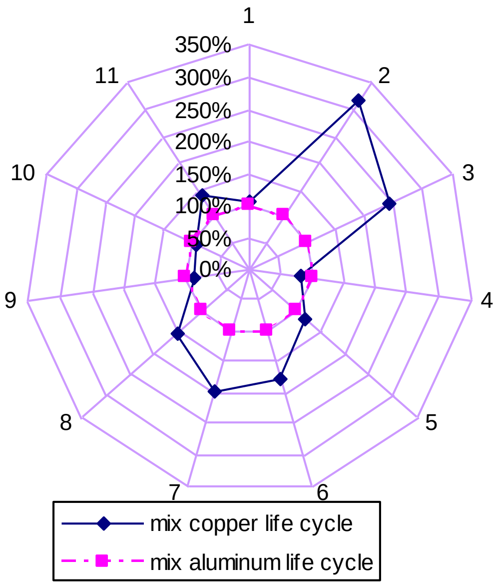

Fig. 2. Environmental impacts of copper or aluminium conductors from a mix of primary (50%) and secondary (50%) resources.

4. Comparison of two machines with same efficiency

Induction machines are often made with cage rotors which conductors are bars and short-circuit rings. Those conductors are generally manufactured with cast aluminium. But it is possible to inject copper instead of aluminium. Several authors have studied the influence of a copper cage on induction machine performances. They generally conclude that the construction is more complex, but that copper cage reduces joule and ventilation losses, and reduces the slip [5] [6] [7] [20] [21]. For the same section and length, the resistance of the rotor conductors is 39% lower and the associated Joules losses. For the same resistance and losses, the section of a copper bar is 39% lower.

Use of copper instead of aluminium involves a few problems [8] [22]. The material used for the rotor is highly stressed during the die-casting of the bars at the copper melting temperature (1083°C). This high temperature and the required pressure consume more energy. The temperature can also degrade the quality of the magnetic rotor sheets if the process is poorly controlled. For same dimensions, motors with copper rotor have a starting torque lower and a higher starting current. Then in some applications a modified design of rotor slots or a soft starter needs to be used. The higher copper rotor weight increases the motor inertia. In that case, it can be a problem for variable speed or an advantage for some constant speed applications.

Despite these few remarks, the copper rotor motor is now a well-known and accepted technology for many applications.

An interesting LCA study [14] was performed in 2010 for the firm FAVI which is able to build copper-cage using an injection presses. This study compares two 3kW induction machines with the same IE2 efficiency (85.5% according to IEC 60034-30 standard): one with a copper-cage rotor and the other with an aluminium-cage rotor. As the losses are identical for the two machines, and supposing the same lifetime, it is not useful to consider the use phase. We repeated this LCA study, with the same parameters (Table 2).The figure 3 compares our results about the environmental impacts of the two machines, concerning only the manufacturing and the end of life. The conclusion is similar to those of the FAVI study: it can be observed that the impacts of the machine with copper rotor are lower for 8 criteria among 11.

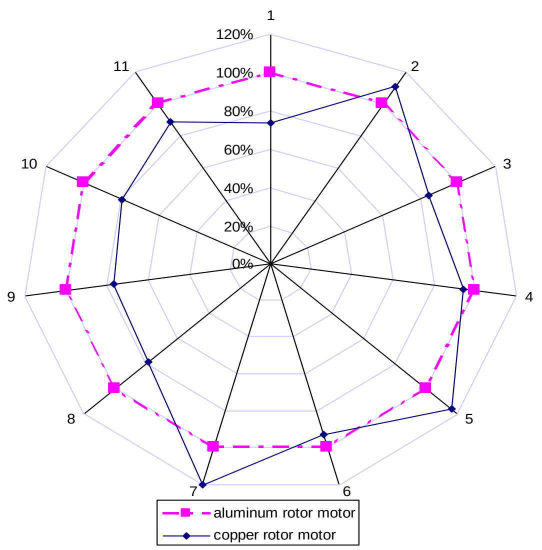

Fig. 3. *Environmental impacts of two 3kW induction machines, with copper or aluminium rotor conductors.*

Nevertheless it is difficult to have a definitive opinion only regarding this comparison: the differences are small, and we compared two machines with different housings: the housing of the machine with copper rotor is made with aluminium, while this of the machine with aluminium rotor is made with cast iron. The masses are very different. So we compared the two machines without housings. The results are given Fig. 4.

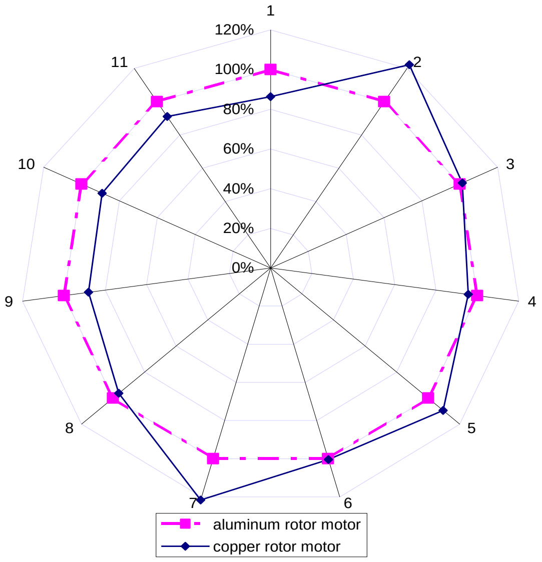

Fig. 4. *Environmental impacts (construction and end of life) of two 3kW induction machines, with copper or aluminium rotor conductors and without housings.*

The conclusions are similar. The environmental impacts of the motor with copper-cage rotor are lower. Nevertheless, the impacts of the machine with copper rotor are lower for only 6 criteria among 11, and the differences are smaller than for the previous study.

The principle of this comparison is: a motor made with copper-cage rotor is, for the same efficiency, smaller and lighter than a motor made with aluminium-cage rotor. It can be observed than the mass of the stator conductors and electrical steels are larger with the aluminium rotor machine. For the manufacturing, environmental impacts are greatly influenced by the metals mass, the heaviest motor is the worst.

Indeed, the motor designers have many areas of improvement in order to obtain a same efficiency (especially to achieve an IE-2 standard): improve magnetic materials, change the sheets stack, the stator winding, the lamination and even all the motor dimensions as examples [14].

According to [9], for powers less than 10kW, reaching the standard of IE3 motors with aluminium rotor is technically feasible and cheaper than with a copper rotor. Only the economic cost of active parts is included in this study. As copper injection is more expensive, the initial cost is higher.

The same study shows that the mass difference of the active parts is small (about 6-10%). Consequently, with a closer mass the environmental assessment difference between motors is always small. As the specific construction processes are not well-known it is difficult to choose between copper and aluminium for the same efficiency.

5. Comparison of two identical machines with different rotors

To study the differences of environmental impacts between copper-cage rotor and aluminium-cage rotor without the influence of the other parts of the motor, another way is used: two identical motors except for their rotor are considered. For construction and end of life, the environmental impacts of the stators are identical. So the error made on many parameters has less consequences. However with this comparison the use phases are different and need a careful analysis.

5.1. Construction and end of life

The reference motor made with an aluminium-cage rotor is described in [23] [25]. In our study copper replace the 2.1 kg aluminium of the cage rotor. As the copper density is 3.28 higher than that of aluminium, the weight of the copper-cage rotor is 6.88kg. A total of 10.32kg of copper is necessary because of the process losses [14]. The description of the copper-cage motor will be the same than the aluminium one, except for the first line of table 3 that will be replaced by the table 4 description.

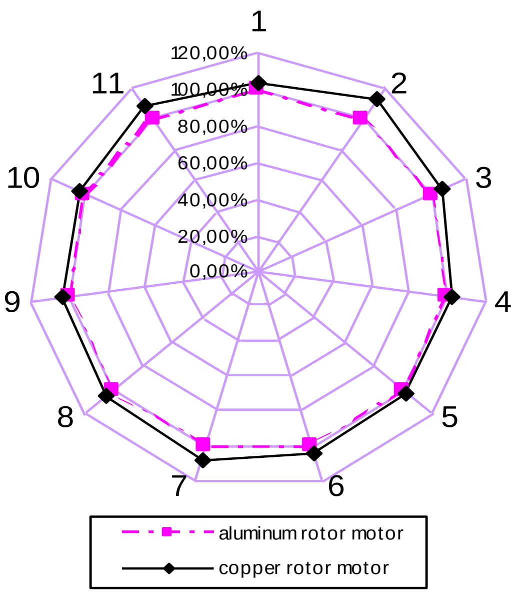

Fig. 5. *Construction and end of life environmental impacts of two almost identical 10kW induction machines made with a copper or aluminium cage rotor.*

The environmental model, using mainly generic data, is difficult to make, because the origin of materials and real processes can be extremely different from a motor to another one. The influence of these variations is important. Some materials, like electric steel (silicon alloy steel), do not exist in the data bases and some elements (transport for example) are unknown and therefore ignored. The real impacts are likely to be more significant than those modelled but, as the two motors are identical except for the rotor-cage material, the relative comparison is still relevant.

Complete results are shown on Tables 7 and 8. The figure 5 concerns only the construction and the end of life: it shows that the environmental impacts of copper rotor motor are slightly higher than these of the aluminium rotor motor. This result can be explained because of the higher mass of the copper.

The end of life phase depends only on the material mass and the recycling rate indicated on Table 5. As expected in previous analyses, environmental impacts of this phase are small by comparison of construction impacts.

The rotor-cage replacement has an average impact difference of 5% as shown in Fig. 5 and Tables 7 and 8. It is not negligible but the use phase can offset these results.

5.2. Use Phase

Table 6 and Fig. 6 show the electrical information of the aluminium rotor motor used as reference model [17].

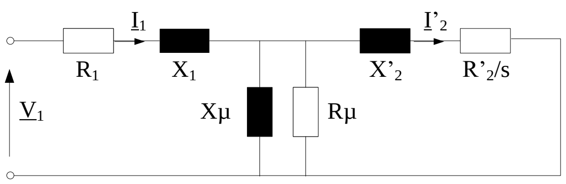

Fig. 6. *Single-phase equivalent circuit of induction motor.*

The aluminium rotor resistance is R'2=0.45Ω. As the resistivity of copper is lower, the resistance of copper rotor is lower: R'2=0.2732Ω (the resistivity ratio between copper and aluminium is 17/28). So the torque curves versus the slip are different, as shown on Fig. 7 (and the start torque is lower with a copper rotor). Consequently the evolution of the useful power versus speed is different for the two machines (Fig. 8). The influence of the supply, PWM inverter or grid, is negligible because our study concerns the rotor.

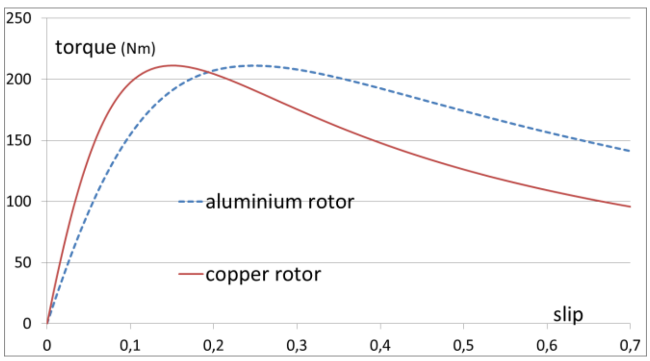

Fig. 7. *Torque (Nm) versus slip for aluminium and copper rotor.*

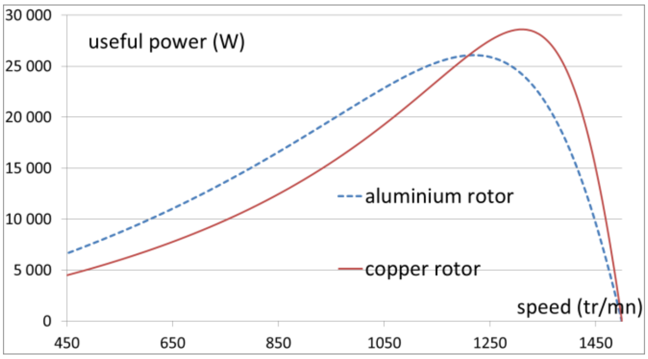

Fig. 8. *Useful power versus speed for aluminium and copper rotor.*

The figures 9 and 10 show the efficiency for for a speed range corresponding to a useful power close to the rated power (10kW). It can be seen a better efficiency with copper rotor.

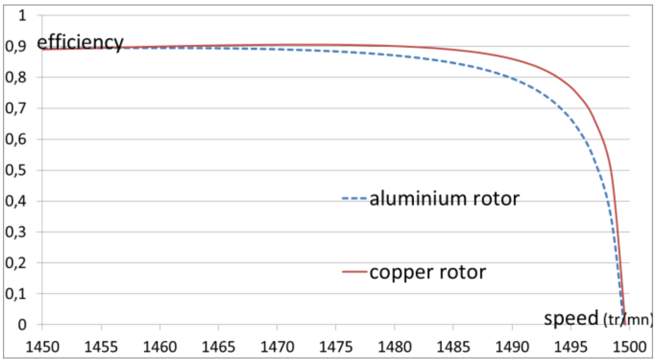

Fig. 9. *Efficiency versus speed for aluminium and copper rotor.*

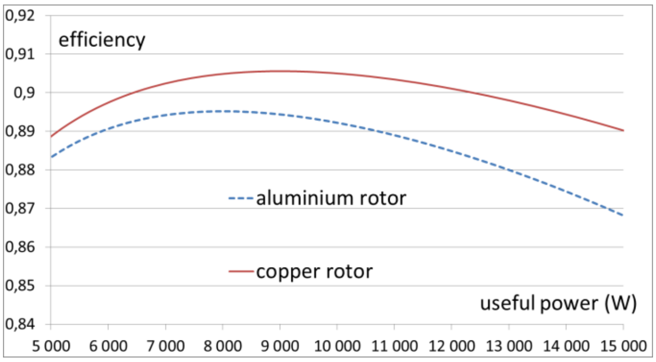

Fig. 10. *Efficiency versus power for aluminium and copper rotor.*

For the same mechanical power (10kW), the efficiency is 89,19% with aluminium-cage rotor and 90,48% with copper-cage one. The total losses are respectively 1224W and 1066W. So with a copper-cage rotor, for the same mechanical power, the losses are reduced by 158W, they are 13% lower.

Multiply the losses by the use time allows to assess the use phase environmental impacts. In a first step, selected impacts are those of the French electricity (Electricity, low voltage, production FR, at grid / FR S). In a second step, those of European electricity are considered (Electricity, low voltage, production UCTE, at grid / FR S).

Obviously the results depend mainly on the time of use. To illustrate two examples are showed: 2 000 hours, a classic washing machine domestic use and 20 000 hours, a classic industrial use.

For a low usage time (2 000 hours) and a French electricity, Fig. 11 shows that, for most criteria, the two motors have roughly the same environmental impacts. If the time becomes lower (i.e. motor automatic gate), the copper rotor motor becomes gradually worse for environmental purpose.

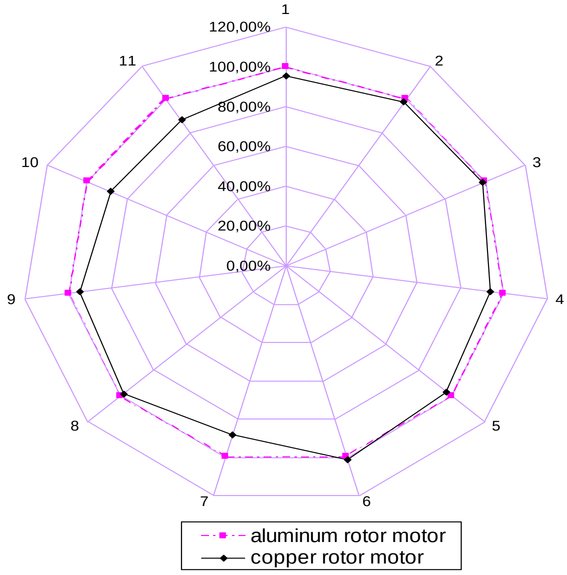

Fig. 11. *Life cycle environmental impacts comparison between the copper rotor motor and the aluminium rotor motor with 2 000 hours of use, french electricity.*

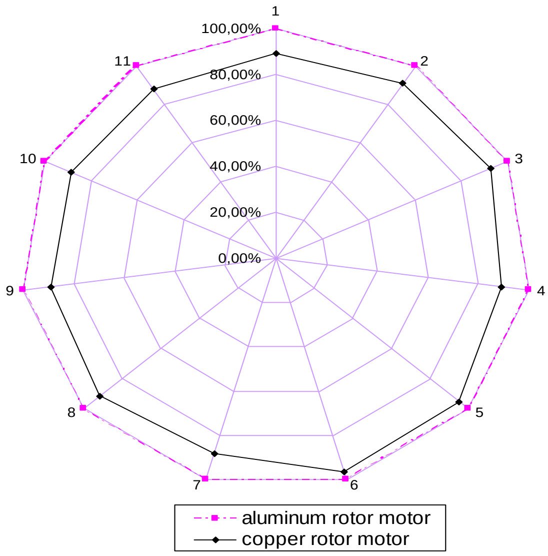

Fig. 12. *Life cycle environmental impacts comparison between the copper rotor motor and the aluminium rotor motor with 2 000 hours of use, european electricity.*

This finding is influenced by the origin of electricity as showed on Fig. 12. With European electricity, the copper rotor motor remains better with a low usage time. The differences can be explained by the electricity origin: french electricity comes at 94%, from nuclear power plants and renewable sources while in Europe the electricity comes from more than 50% from fossil power plants. So French electricity generates more ionizing radiations (criteria n° 11) but less others impacts (above all IPCC and Abiotic depletion). Consequently the impacts of the use phase are higher in other countries than in France, and the differences between copper and aluminium are more important.

For an industrial use time (20 000 hours), Fig. 13 shows that the losses reduction with a copper rotor generates better results. In that case the construction, the end of life and the electricity origin have a negligible influence

These results show that total environment impacts of a copper rotor motor are lower. If this motor is heavy used, the higher construction impacts are negligible. Maybe this technology is not often used because motor manufacturers have others cheaper technologies to obtain the efficiency needed by the IE2 and IE3 efficiency standard.

However if an aluminium rotor motor can achieve IE3 standard, the same motor with a copper rotor will be even better with lower environmental impacts and perhaps reach future IE4 standard.

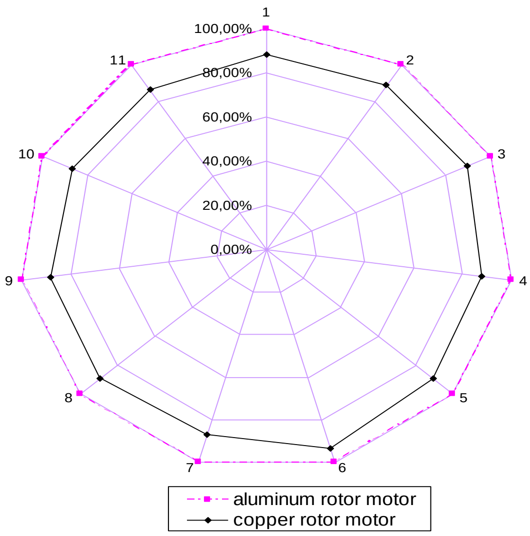

Fig. 13. *Life cycle environmental impacts comparison between the copper rotor motor and the aluminium rotor motor with 20 000 hours of use.*

6. Conclusion

This Life Cycle Analysis tries to compare environmental impacts of two technologies. The comparison is not easy because it is very difficult to really know the used processes and materials in different firms in order to quantify their impacts. For example the first comparison of this paper shows that the influence of the recycling is very important but it is often difficult to know if the manufacturers really use recycled materials.

On the other hand the interpretation of the results depends on the chosen environmental criteria, and on the origin of energy depending on the country. For example, is it more important to have less ionizing radiations or less impact on climate change?

Nevertheless some clear conclusions can be drawn:

- the environmental impacts of construction and end of life of a copper-cage rotor are worse than for an aluminium one,
- the environmental impacts of the use phase are better with a copper-cage rotor because of fewer losses,
- the total environmental impacts are better with a copper rotor if the machine is heavily used.

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8. Appendices

Table 1 List of impact criteria

N°	impact criteria	Unit	Comment
1	Abiotic depletion	kg Sb eq.	Determined for each extraction of minerals and fossil fuels; it corresponds to non-renewable resources expressed with a reference to a standardized rare material: the antimony (Sb). The unit is the equivalent mass of Sb
2	Acidification	kg SO_2 eq.	Corresponds to the acidification of soils, water and air, it is expressed considering the equivalent mass of sulphur dioxide
3	Eutrophication	kg PO_4 eq.	Related to the concentration of nutrients, especially phosphates and nitrates, in an aquatic environment, which disturbs the natural growth of plants. It is expressed considering the equivalent mass of phosphate
4	Ozone layer depletion	kg FC_{11}eq	Defines the ozone depletion potential of different gasses, it is expressed considering the equivalent mass of trichlorofluoromethane
5	Human toxicity	kg 1.4 DB eq.	Expresses human toxicity potentials (HTP), for each toxic substance. It is also expressed considering the mass of an equivalent toxic product
6	Water pollution	kg 1.4 DB eq.	Similar to the previous one but it concerns only fresh water
7	Terrestrial eco-toxicity	kg 1.4 DB eq.	This indicator is similar to the previous one but it concerns the pollution of soils
8	Photochemical oxidation	kg C_2H_4 eq.	Related to a reference substance which has a detrimental action on photochemical oxidation
9	IPCC (100 years)	kg CO_2 eq.	The Intergovernmental Panel on Climate Change was established by the United Nations Environment Programme and the World Meteorological Organization
10	Cumulative Energy Demand	MJ	This indicator computes the total energy used to build an equipment, it is expressed in mega joules
11	Ionizing radiation	Sv eq.	Ionizing radiations are expressed in Sievert for evaluating impacts on humans.

Table 2 List of process and materials used with two 3kW machines, one with aluminium rotor, one with copper rotor

machine part	process and materials from Ecoinvent database	quantity with copper rotor	quantity with aluminium rotor
Rotor material		7.045kg	8.075kg
primary copper	Copper, primary, at refinery/RER	2.77kg	
secondary copper	Copper, secondary, at refinery/RER	1.13kg	
primary aluminium	Aluminium, primary, at plant/RER		0.0973kg
secondary aluminium	Aluminium, secondary, from new scrap, at plant/RER		0.8757kg
rotor electrical steel	steel, converter low-alloyed, at plant/RER	4.475 kg	7.101 kg
Rotor process			
copper injection and rotor machining	Electricity, medium voltage, production UCTE, at grid/UCTE S	37 MJ	
aluminium cast and rotor machining	Electricity, medium voltage, production UCTE, at grid/UCTE S		35.5 MJ
steel rolling	Sheet rolling, steel/RER	4.475 kg	7.101 kg
Stator material		18.625kg	29.31kg
primary copper	Copper, primary, at refinery/RER	0.498kg	0.719kg
secondary copper	Copper, secondary, at refinery/RER	1.992 kg	2.876kg
stator electrical steel	steel, converter low-alloyed, at plant/RER	10.19 kg	12.62kg
Bearings	Steel, low-alloyed, at plant/RER	3 kg	3,09kg
housing primary aluminium	Aluminium, primary, at plant/RER	0.2945kg	0.01kg
housing secondary aluminium	Aluminium, secondary, from new scrap, at plant/RER	2.6505kg	0.09kg
iron housing	pig iron at plant/GLO		9.905kg
Stator process			
copper process	Wire drawing, copper/RER	2.49 kg	3.595kg
steel rolling	Sheet rolling, steel/RER	10.19 kg	12.62kg
bearing rolling	Sheet rolling, steel/RER	3 kg	3.09kg
bearing machining	Electricity, medium voltage, production UCTE, at grid/UCTE S	10.43734MJ	10.75 MJ
aluminium casting (housing)	Electricity, medium voltage, production UCTE, at grid/UCTE	20.223MJ	
iron casting (housing)	Electricity, medium voltage, production UCTE, at grid/UCTE		31.13MJ

1 : 34% of copper is lost during the injection process, i.e. 1.33 kg of copper lost recycled

Table 3 List of process and materials used with 10kW machine with aluminium rotor

Material	Ecoinvent Data
Aluminium Rotor 2.1 kg secondary 66% primary 33%	Aluminium, secondary, from old scrap, at plant/RER S Aluminium, primary, at plant/RER S Electricity, medium voltage 42 MJ, production UCTE, at grid/UCTE S for Injection and machining [17]
Aluminium Other 0.6 kg secondary 66% primary 33%	Aluminium, secondary, from old scrap, at plant/RER S Aluminium, primary, at plant/RER S Sheet rolling, aluminium/RER S
Electric steel : 33.7 kg stator :28.4 kg rotor 5.3 kg	Steel, converter low-alloyed, at plant/RER S Sheet rolling, steel/RER S Hot rolling, steel/RER S
Other steel 31.5 kg	Steel, low-alloyed, at plant/RER S Sheet rolling, steel/RER S Electricity, medium voltage, 109 MJ, production UCTE, at grid/UCTE S for machining
Stator Copper 4.3 kg	Copper, primary, at refinery/RER S Wire drawing, copper/RER S
Insulation 0.1kg	Polyamide-imide, Polyester-imide Burn Solvants [ref] Electricity, medium voltage 16MJ, production UCTE, at grid/UCTE S [19]
Impregnation resin 1kg	polyester resin unsaturated at plant /rer s Burn Solvant [19]
Other Plastic 0.3kg	Polyvinylchloride at regional storage rer s Injection moulding/RER S

Table 4 Specific process and materials used with 10kW Copper rotor machine

Material	Ecoinvent Data
Copper Rotor 10.32 kg used (for 6.88 kg in finished rotor) Secondary 66%; primary 33%	Copper, primary, at refinery/RER S Copper, secondary, at refinery/RER S Electricity, medium voltage,75 MJ production UCTE, at grid/UCTE S for Injection and machining [17]

Table 5 End of life Data

Material	End of life scenario
Aluminium	90% recycling, 10% Landfill/CH S
Steel	45% recycling, 55% Landfill/CH S
Copper	80 % recycling, 20% Landfill/CH S
Plastics	Waste scenario/FR S

Table 6 Parameters of the single-phase equivalent circuit of the 10 kW reference aluminium-cage rotor motor

Parameter	R_1	X_1	Xμ	Rμ	R'_2	X'_2	Mechanical losses
Value (Ω)	0.42	0.93	23.4	475	0.45	0.87	75W

Table 7 Aluminium Rotor Motor, 20 000 hours

		Construction phase	End of life phase	Use phase French electricity	Use phase UCTE electricity
1	Abiotic depletion	1.85E+00	2.50E-03	1.70E+01	1.06E+02
2	Acidification	1.23E+00	1.66E-03	1.65E+01	7.05E+01
3	Eutrophication	1.61E-01	3.64E-03	1.08E+00	3.68E+00
4	Ozone layer depletion	1.04E-05	5.28E-08	1.15E-04	6.34E-04
5	Human toxicity	4.93E+02	5.35E-01	2.53E+03	4.18E+03
6	Water pollution	1.51E+02	2.50E+00	2.12E+02	1.04E+03
7	Terrestrial eco-toxicity	2.30E+00	3.35E-03	2.25E+02	2.64E+02
8	Photochemical oxidation	1.04E-01	1.74E-04	6.38E-01	2.76E+00
9	IPCC (100 years)	2.24E+02	1.31E+00	2.55E+03	1.44E+04
10	Cumulative Energy Demand	3.85E+03	6.16E+00	3.31E+05	3.09E+05
11	Ionizing radiation	6.65E+03	7.94E+00	3.19E+06	1.19E+06

Table 8 Copper Rotor Motor, 20 000 hours

		Construction phase	End of life phase	Use phase French electricity	Use phase UCTE electricity
1	Abiotic depletion	1.93E+00	2.65E-03	1.48E+01	9.24E+01
2	Acidification	1.40E+00	2.02E-03	1.43E+01	6.12E+01
3	Eutrophication	1.68E-01	7.14E-03	9.38E-01	3.20E+00
4	Ozone layer depletion	1.06E-05	5.66E-08	9.96E-05	5.50E-04
5	Human toxicity	5.02E+02	7.79E-01	2.19E+03	3.63E+03
6	Water pollution	1.54E+02	5.16E+00	1.84E+02	9.01E+02
7	Terrestrial eco-toxicity	2.47E+00	5.36E-03	1.95E+02	2.29E+02
8	Photochemical oxidation	1.09E-01	3.57E-04	5.54E-01	2.39E+00
9	IPCC (100 years)	2.32E+02	2.27E+00	2.22E+03	1.25E+04
10	Cumulative Energy Demand	4.00E+03	6.62E+00	2.87E+05	2.68E+05
11	Ionizing radiation	7.25E+03	8.94E+00	2.77E+06	1.03E+06