Comparative LCA of NdFeB and ferrite motors used in the microfabrication industry

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The goal of a microfactory is to manufacture small-scale products and realize an associated reduction in space, energy, and materials in comparison to traditional factories. The creation of a microfactory requires the miniaturization of manufacturing equipment, which in turn necessitates the development of compact actuators and other components. In this regard, motors that use magnets based on such Rare Earth Elements (REEs) as Neodymium and Dysprosium are being widely used. Motors based on REEs offer several advantages relative to motors based on conventional materials, including a smaller mass and volume. Owing to these advantages, REEs are being adopted in an ever growing number of applications. The increased use of REEs is placing more attention on their availability, production, and environmental impact. This paper presents the results of a life cycle assessment (LCA) of a REE motor and compares these results to a motor that utilizes conventional materials. Also to be discussed are issues surrounding availability and supply chain disruption.

NOMENCLATURE

LCA = life cycle assessment
REEs = rare earth elements
REOs= rare earth oxides
REPMs= rare earth permanent magnets

1. Introduction

Microfactories are miniaturized or downsized manufacturing systems with an emphasis on automation. Microfactories can be developed to manufacture miniature components that are difficult to manufacture through conventional factories. Miniaturized components are utilized in many industries including aerospace, biomedical, defense, and electronics (Honegger et al., 2006). These systems allow for a reduction in energy, materials, space, and time. Microfactories offer exceptional flexibility to the manufacturing processes, greater position accuracy, precise manufacturing, and strive to be eco-friendly. Additionally, given their flexibility and potential for mobility, microfactories can be used for customized products and for point-to-need manufacturing.

However, there are disadvantages associated with microfactories. Machine components are difficult to manufacture, so they come with a higher cost. Furthermore, there are requirements for special working environments in the factories, e.g., miniaturized instrumentation for process monitoring. Another important property of microfactories is that it is not just a scaled down version of a traditional factory. For manufacturing equipment employed in a traditional factory, the size of the various components that form the equipment is generally not a critical concern. For the micro manufacturing equipment (or micromachines) of microfactories, however, space utilization is of great importance.

For this reason, there is a need for compact actuators and other components to form such micromachines as micro mills, micro drills, and micro laser processing systems. However, reduction in the sizes of the components must be done with a concern for the efficiency of the manufacturing process. Servomotors are a class of motors used for precision control of motion and position. Typically, a servomotor is coupled with a sensor that continually provides inputs/outputs between the motor and controller. A typical brushless servomotor configuration can be seen in **Figure 1**. The different

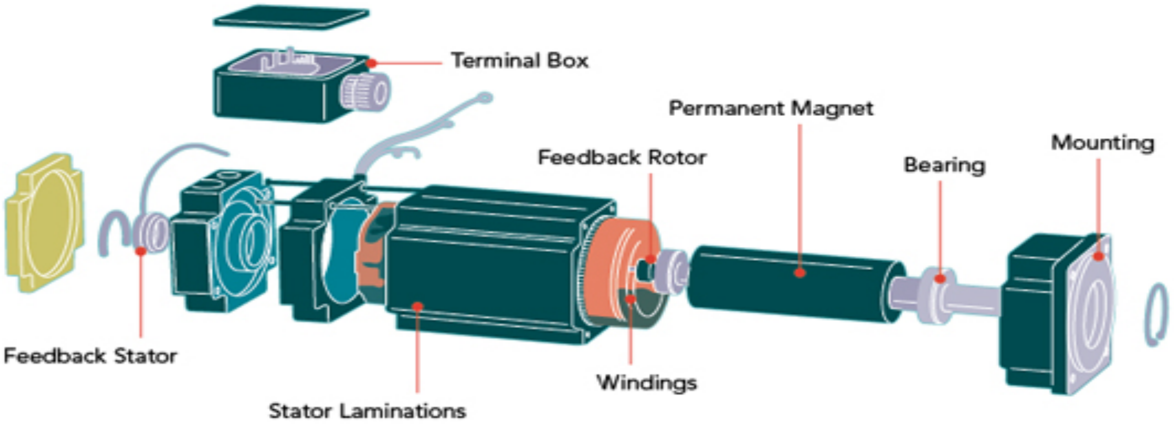


Fig. 1 Basic components of servomotors (Musta'in, 2010)

components of the motor include: rear cover, feedback stator, terminal box, stator, rotor, copper windings, permanent magnets, bearings, grease, retaining rings, and clamps. A servomotor can be utilized in variety of applications, e.g., manufacturing, automotive, and aerospace. Certainly, servomotors are widely in use in machine tools. With micromachines, there is a need for servomotors with high-strength magnets within a small volume. Such high strength is available with rare earth permanent magnets (REPMs) that are based on rare earth elements (REEs).

The use of REEs in technological applications has been expanding. The unique properties of REEs have led to their use in technologies that save on energy and resources. REEs are 17 elements that have similar physical and chemical properties. They are comprised of the 15 elements that make up the Lanthanide group (57-71) of the periodic table, and include Scandium (21) and Yttrium (39). The paths for typical REE extraction to purification follow the similar scheme of mining, physical beneficiation, chemical treatment, separation, and reduction, refining and purifying (Gupta and Krishnamurthy, 2005). Currently, there are three main sources or routes for REE production: Bayan Obo (China), Mountain Pass (U.S.), and Ion-Adsorption Clays (Southern China).

REEs are not actually rare in the soils, but they have low concentrations. In fact, they are more abundant than gold and copper. There are significant REE deposits globally, yet China has dominated REE production. Currently, China is providing in access of 85% of the global REE supply, and over 90% of purification is taking place in China (EPA, 2012). REEs are not manufactured without a substantial cost: both financial and environmental. Citing environmental concerns as the main reason, in 2008 China began to implement production and export quotas for rare earth oxides (REOs) and REEs. For this reason, REO and REE prices have risen sharply on occasion (Walters et al. 2010) and their price remains volatile.

The rise in raw material prices has caused governments and countries to examine where and how they receive their inventory. This has meant a rise in concern of the availability of the REEs and REOs. The United States, Japan, and the European Union have examined resources and developed plans to account for future shortages and disruptions to supply chains. According to Golev et al. (2014), companies such as Honda and Toyota have future initiatives to meet their REE needs by as much as 10% from recycled materials. Recently, exploration of sites suitable for the mining of REEs has been examined and closed mines, e.g., Mountain Pass, have resumed production (EPA, 2012).

Applications for REE use include energy efficient lighting, energy storage, and rechargeable batteries. Another very important use for REEs is in permanent magnets. Motors containing REPMs can be used in wind turbines, electric vehicles, and anywhere that needs a high-powered magnet (Dent, 2012). The REE Neodymium has been identified as an important element for use in producing high-strength, i.e. high remanence, high coercivity, and higher energy product, magnets in combination with iron, boron, and small quantities of dysprosium (Brown et al., 2002). The properties of the NdFeB magnets allow for the use of motors with higher magnetic properties with a reduction of volume compared to traditional ferrite magnet motors (Akahori et al. 2014). For that reason, NdFeB magnets have become the industry leader for high-strength motors. The ability to reduce the size of many components gives them an advantage over the more traditionally used ferrite magnets; however, ferrite magnets are still widely used because of their low costs.

In spite of their high cost relative to ferrite magnets, NdFeB magnets are an attractive alternative owing to their compactness. However, given the foregoing comments related to REE use (benefits in terms of energy and resource saving) and environmental impact of mining and processing, it is appropriate to make an environmental comparison of ferrite and NdFeB magnet based motors. An environmental Life Cycle Assessment (LCA) of the two motor types is an important step to determine the environmental impact of both assemblies. In this way, companies involved in the development of micromachines who are concerned with the environmental impacts of their products, can make an informed decision on which motor type fits their needs. In addition, decision-makers with an interest in sustainability or in the promotion of green technologies can have access to valuable information relating to the environmental footprint of servomotors. In recent times, LCAs have become a core element in environmental policy globally (Guinee et al., 2010).

2. Methodology

There are four main steps to an LCA study: i) Setting of Goal and Scope, ii) Life Cycle Inventory (LCI) Analysis, iii) Life Cycle Impact Assessment (LCIA), and iv) Interpretation as can be seen in **Figure 2**. This comparative study will follow the ISO-14040 series guidelines (ISOb, 2006).

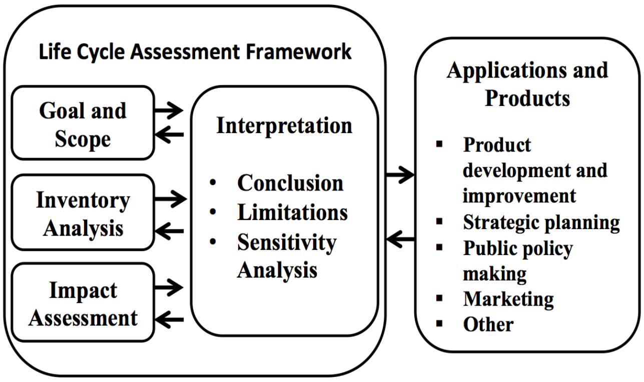


Fig. 2 LCA steps (ISO, 2006)

2.1 Goal and Scope

According to the ISO (2006a), the goal and scope step of an LCA is where the study will be defined. In this step, the boundary will be set and the stakeholder for whom the study will be performed will be determined. This step also involves determining the functional unit. Essentially, this allows fair comparison to be made among alternatives. With the goal of the study being to perform a comparative LCA on two motors that can be used as part of a micromachine, two types of servomotors from a major manufacturer were identified. These motors differ in term of the permanent magnet materials they utilize, and other components and materials also vary in terms of their weight (mass). There are many standard parts being used both assemblies.

A servomotor based on the NdFeB REE is being considered for this study. The motor consists of Neodymium, Iron, Boron, and small amounts of Dysprosium. The composition for the motor under investigation is 72% Fe, 27% Nd, 1% B, and the amount of Dy considered as negligible since it was not present to a significant extent. NdFeB magnets offer the advantage of having a higher torque within a smaller volume (relative to a traditional motor); however, the higher costs of the REEs make the magnet prices higher.

For the hard ferrite permanent magnet motor used in this study, the composition of the magnet is iron and either barium carbonate or strontium carbonate. Both of these metals are part of the alkaline earth metals group. The composition of the motor under investigation was determined to be 90% Fe and 10% alkali. Motors based on a ferrite magnet are used for inertia matching purposes and because of their lower costs.

Since the purpose of this study was to perform a comparative LCA between a motor containing REEs and a ferrite containing motor, a functional unit must be defined. Ferrite and NdFeB magnets are very stable, therefore both motors' components were considered to be the same with the exception of their magnets. In addition, it was assumed that both motors would have the same service life. Therefore, the functional unit of the study was defined as a one servomotor possessing 4.5 Nm of torque designed for high temperatures and moisture and dust resistance needed for use as a component in a micromachine.

For the system boundary of the study, it was determined to employ a cradle-to-gate assessment of the two technologies. Such an assessment considers the life cycle from time raw material is extracted until the manufacturer ships the motor to the user. Given the similarity of the identified motors, their use phase was not considered for the LCA. These motors were identified with the help of industry partners who work in the servomotor industry. A diagram of the system boundary can be seen in **Figure 3**.

After the appropriate major material and energy flows of the life cycle stages under consideration are tabulated, they are evaluated using the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) impact assessment method. TRACI is a widely accepted method for the use in conducting LCAs. TRACI uses a midpoint approach for LCIA calculations. This is a problem-oriented approach that stops at the midpoint of the cause-effect chain. The categories TRACI uses for analysis are: global warming (kg CO_2-Eq), acidification (H+ moles-Eq), cancer effects (kg benzene-Eq), non-cancer effects (kg toluene-Eq), respiratory effects (kg PM2.5-Eq), ozone depletion (kg CFC-11-Eq), smog formation (kg NO_x-Eq), ecotoxicity (kg 2,4-D-Eq), and eutrophication (kg N-Eq).

2.2 Life cycle inventory analysis

For the LCI portion of an LCA, the type of analysis is determined and the software or methodology to be employed is also identified. Furthermore, the inputs and outputs of the different processes are compiled. Careful consideration of materials, masses or weights, and processes should always be taken to ensure accurate results.

Material and energy resources are consumed during the manufacture of the motors. These inputs come from both renewable and nonrenewable resources, where outputs in the form of air, water, and solid wastes are generated. The LCI model in this study was generated using the SimaPro version 7.1 software and the Ecoinvent 2.0 database. When applicable, Chinese processes were used since much of the servomotor manufacturing is likely performed in China; however, given the limitation of the database (much Chinese data not available), global and European processes were used as well.

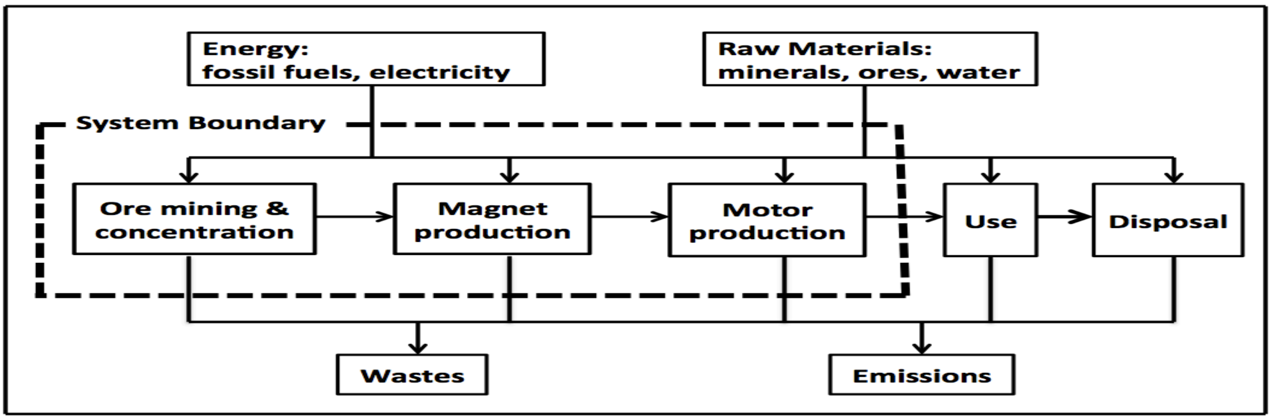


Fig. 3 System boundary for servomotors

To augment the limitations of the databases, literature on REE and NdFeB magnet production was used. Sprecher et al. (2014) were able to develop the production chain of NdFeB magnets using existing processes in the Ecoinvent database and adding processes from literature and experiments. Through this, they were able to develop a comprehensive LCI process for NdFeB magnets. For the ferrite magnet production process, an existing process form Ecoinvent was used and manipulated based on data from research. It should be noted that the ferrite magnet may be missing processes. **Table 1** and **Table 2** list the different processes used to produce the components and assemble the two motors. Given the complexity of processing REEs, and more specifically Neodymium, the NdFeB magnet has many more listed processes. Other processes were identified in the Ecoinvent database, and the appropriate masses gathered via communication with industry contacts working in the micromachine, automation, and servomotor industries were used.

Table 1 Different processes for NdFeB motor assembly

Motor Type	Process
NdFeB	
Magnet assembly	Mining of REE containing ore
	Beneficiation of REE ore
	REE acid roasting
	REE leaching
	REO solvent extraction
	Liquid neodymium, primary
	Neodymium, primary
	NdFeB strip casting, primary
	Hydrogen decrepitation, primary
	Jet milling, primary
	Aligning and pressing of NdFeB, primary
	Vacuum sintering of NdFeB, primary
	Grinding and slicing of NdFeB, primary
	NdFeB electroplating, primary
	Pulse magnetizing and testing of magnet
Coil assembly	
	Copper, at regional storage
	Wire drawing, copper
Laminated steel	
	Steel, low-alloyed, at plant
	Steel product manufacturing, average metal

Table 2 Different processes for ferrite motor assembly

Motor Type	Process
Ferrite	
Magnet assembly	Ferrite, at plant
	Grinding and slicing of ferrite
	Coil assembly
	Wire drawing, copper
	Ferrite, at plant
	Grinding and slicing of ferrite
Coil assembly	
	Copper, at regional storage
	Wire drawing, copper
Laminated steel	
	Steel, low-alloyed, at plant
	Steel product manufacturing, average metal

The major differences in the motor assemblies are the magnet material composition and mass, copper winding mass, and laminated steel mass. For the laminated steel, this is the mass of the steel used in manufacturing (from a coil input), and is not the mass in the motor assembly. Materials such as grease and sensors were excluded from the study, since they are either standard parts or the difference in their masses is small. Other components and processes for the motors excluded from the study included the nameplate, powder coating, sensor wires, rings, and clamps for the aforementioned components.

The table of components and properties of the two motors is provided in **Table 3**. Given their stronger magnet fields, the NdFeB magnet motor uses less than half the volume and mass of the ferrite magnet motor. Additionally, the NdFeB magnet weight is less than one third the ferrite motor weight. Finally, the copper wire is more than half the weight of the ferrite motor. With the reduction in size of many components, the NdFeB motor still possesses a greater torque and peak torque than that of the ferrite magnet-based motor.

Table 3 Comparison of properties between REE motor and ferrite motor

Properties	NdFeB	Ferrite
Magnet Material (element)	REE (NdFeB)	Ferrite (Fe_xO_y)
Torque (N*m)	4.52	4.30
Peak Torque (N*m)	18.08	12.95
Motor Length (cm)	21.41	23.77
Motor Width (cm)	8.00	10.92
Motor Height (cm)	8.89	11.94
Motor Volume (cm^3)	1523.03	3099.87
Servomotor weight (kg)	6.0	13.6
Magnet Weight (kg)	0.202	0.608
Copper wires (kg)	0.77	1.60
Lamination Steel (kg)	5.85	12.38

A number of assumptions were made when conducting the LCI. It was assumed that there were zero contributions from recycled magnets to the permanent or ferrite magnets masses. For the ferrite magnet composition, there was no data found in SimaPro or Ecoinvent for barium carbonate or strontium carbonate, so another alkali earth metal (i.e., magnesium) was used. Additionally, the same shaping and slicing process as for NdFeB magnet production was used for ferrite magnets to account for losses. For the copper wiring, the pre-existing process in Ecoinvent was used. Finally, for the steel used in the motors, an Ecoinvent process for steel was combined with an Ecoinvent process for manufacturing of steel parts.

2.3 Life cycle impact assessment

For the LCIA section, the compiled LCI information is used and calculations are made. Appropriate interpretation methodologies are employed to perform calculations, and final results are prepared in the form of charts, graphs, etc. These results will provide information for the interpretation phase of the LCA.

For the LCIA section, the results are calculated by the mandatory steps of assigning the LCI results (classification) and calculation of the category indicator results (characterization) as suggested by ISO-14040. Other optional elements of calculating the magnitude of category indicator results relative to reference information (normalization) were not included in this study.

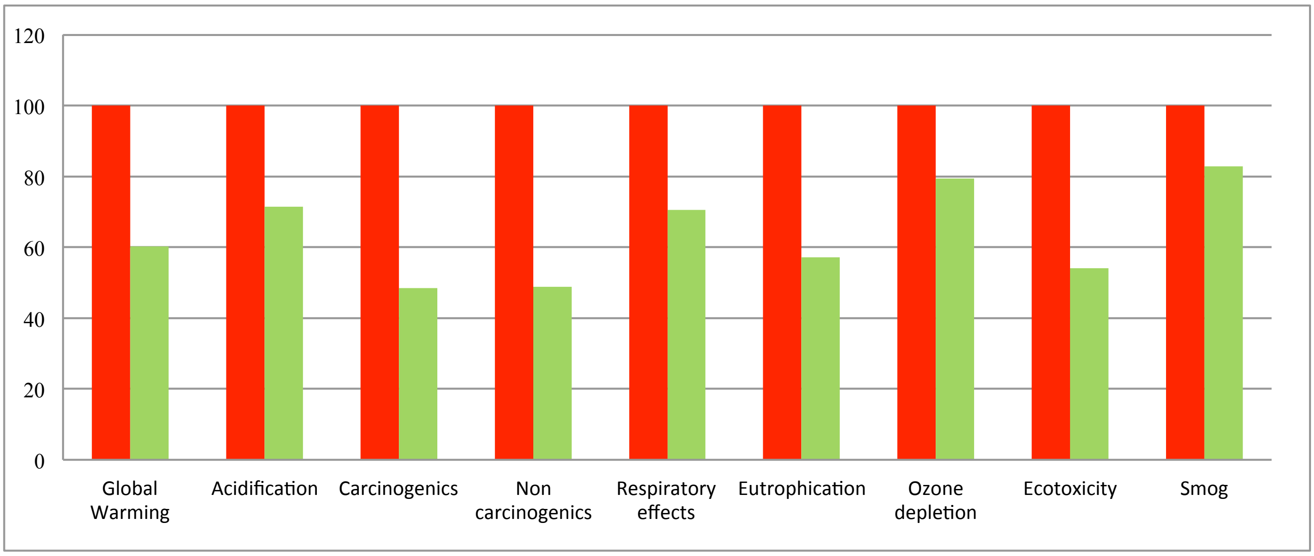
Table 4 compares the life cycle impacts of ferrite magnet motors and NdFeB magnet motors. These are the output results calculated by SimaPro. Again, these results were calculated using the LCIA impact method of TRACI. The ferrite magnet motor has greater impacts in all categories. The biggest differences by percentage according to TRACI are in carcinogens and non-carcinogens. However, the NdFeB magnet has relatively similar impacts in both smog and ozone depletion. Although the NdFeB magnet has a higher environmental impact than the ferrite magnet in terms of a mass-based magnet only comparison, the reduced weight of the magnet combined with the smaller weight of the copper wires and steel in the assembly leads to the NdFeB servomotor having smaller impacts in all categories.

To recap the results of the LCI, out of the nine different impact categories, the ferrite magnets have significantly (i.e., greater than 40%) higher impact in five of the categories. The ferrite motors has higher impacts (i.e., greater than 20% difference) in eight of the impact categories. Finally, ferrite magnet motors have only a slightly higher (i.e., less than 20%) impact only in the smog category.

2.4 Interpretation

Interpretation of results is the final step of an LCA and where the results from the LCIA will be examined. Here all the relevant assumptions and limitations are explained and are ready for analysis as defined by the goal and scope. For the interpretation step, an uncertainty analysis may be conducted, since this will help shed light on where the biggest errors may lie. However, for this study an uncertainty analysis was not

Fig. 4 Impact assessment for ferrite motor (red) and NdFeB motor (green) assemblies using TRACI



performed.

Figure 4 compares the life cycle impacts of the motors by normalizing the impacts of the NdFeB magnet motor (green) to that of the ferrite magnet motor (red). After evaluating the material and energy flows of the two assemblies, the biggest emissions per impact category and processes that contribute the highest impact per category were identified. The biggest emission that affects the global warming category is carbon dioxide from fossil fuel combustion, with the production of pig iron contributing the highest amount. Furthermore, the biggest emission to affect acidification is sulfur dioxide, with the biggest process contribution coming from blasting during mining. Additionally, the biggest emission affecting carcinogens was airborne arsenic, with the biggest impact coming from the disposal process to municipal solid waste and incineration. For non-carcinogens, water contaminated with Lead had the highest emission impact, while the disposal process to highest municipal waste and incineration contributed the most.

Table 4 Life cycle impacts of ferrite magnet motors and NdFeB magnet motors

Impact category	Unit	Ferrite magnet	NdFeB magnet
Global warming	kg CO_2-Eq	76.89	46.3
Acidification	H+ moles-Eq	26.40	18.9
Cancer effects	kg benzene-Eq	3.00	1.46
Non-cancer effects	kg toluene-Eq	8744	4276
Respiratory effects	kg PM2.5-Eq	0.25	0.17
Eutrophication	kg N-Eq	0.072	0.041
Ozone depletion	kg CFC-11-Eq	4.18E-6	3.32E-6
Ecotoxicity	kg 2,4-D-Eq	417.1	225.3
Smog	kg NO_x-Eq	0.20	0.17

For respiratory effects, particulates greater than 10 micrometer to the air had the highest emissions impact, with the largest contributor being the iron ore beneficiation process. Eutrophication had the highest emission impact coming from phosphate distributed to the water, with the disposal to residual material landfills process contributing the most. The biggest emission contributing to ozone depletion came from methane to the air, while the process of natural gas transportation had the highest impact. Finally, for smog formation carbon monoxide to the air had the highest emission impact, with the coal burned in industrial furnaces contributing the greatest amount.

As far as the various processes for the manufacturing of the different motors, the process that contributes the highest impact by volume (m^3) is the drying at the various stages by the use of natural gas. The biggest transportation (ton per km) impact was determined to be by transporting by lorry (truck). As far the processes in terms of kg used, the highest impact was the various water processes used. Overall, the biggest energy contributions in terms of energy (MJ) came in the form of the various processes that consumed electricity. Overall, the consumption of fossil fuels during various processes for energy contributes the highest impacts for both emissions and processes.

Furthermore, it is very important to see how each component is affecting the impact of the overall process for each motor type. Therefore, a contribution analysis was performed for both motors (**Table 5**). Overall, the steel process has the highest environmental impact for both motors. However, the actual amount of impact is different for the two motors. For the NdFeB motor, the magnet contributes a significantly greater amount to the overall impact compared to the ferrite motor in all categories except carcinogens and non-carcinogens. This is due to the Neodymium and NdFeB magnet's large number of processes. The biggest impacts the NdFeB magnet has is in acidification (34.8%), respiratory effects (33.8%), ozone depletion (40.5%), and smog (43.9%). Alternatively, the ferrite magnet production has less than 2.2% of the overall contribution of the motor's environmental impact. The steel process clearly dominates the impact categories for the ferrite motor, contributing no less than 67.9%

Table 5 Contribution analysis of NdFeB motor and ferrite motor

	Warming				Effects		Depletion		
NdFeB motor									
NdFeB magnet	22.8%	34.8%	1.3%	3.3%	33.8%	17.7%	40.5%	12.8%	43.9%
Copper wire	7.2%	29.2%	83.2%	30.0%	18.7%	5.3%	6.3%	27.8%	12.0%
Steel	70.1%	38.3%	15.5%	69.7%	47.5%	77.0%	53.2%	59.4%	44.2%
Sum	100%	100%	100%	100%	100%	100%	100%	100%	100%
Ferrite motor									
Ferrite magnet	1.8%	2.2%	0.1%	0.5%	1.8%	0.5%	0.3%	0.9%	2.0%
Copper wire	8.9%	43.3%	83.9%	27.4%	27.4%	6.2%	10.4%	31.2%	20.6%

in all categories except acidification (54.5%) and carcinogens (16.0%). For NdFeB magnet motors, steel contributes greater than 44.2% in all categories except acidification (38.3%) and carcinogens (15.5%).

For ferrite motors the copper wire process contributes less than 27.4% in all impact categories except for ecotoxicity (31.2%), acidification (43.3%), and carcinogens (83.9%). In all categories, except for non-carcinogens (30.0% to 27.4%), the amount is slightly more for the ferrite motor, since it has a greater copper wire mass than the NdFeB motor. Although the missing components (e.g., rotor, grease, and clamps) for the motors may not greatly influence the various impact category results, they would affect the emissions for the ferrite magnet more, since it has a greater volume. Also, missing steps in the ferrite magnet manufacturing process could result in an underestimation in the results.

3. Discussion

This analysis gives baseline information that can be expanded upon in a further study. The purpose of the study was not an exact environmental impact of the two technologies, but a general view of the different impacts. To have a more complete LCA, further details of the design and manufacturing of the motors is needed. However, this involves having access to information companies keep well guarded. Furthermore, motors with different configurations would have different processes and materials, so any results obtained would naturally be different.

For the analysis, it is clear that the NdFeB magnet has a lower impact in most impact categories. Although the magnet impact for the NdFeB is greater than the ferrite magnet, the larger weight of the other components make up for this in the total assembly. Currently, there is not a feasible substitution for the Nd and Dy in the NdFeB magnets. However, there is ongoing research into improving the manufacturing processes from an environmental standpoint.

In addition, a micromachine would enlist a number of NdFeB or ferrite motors, so whatever LCA results are obtained would have to be multiplied for an entire assembly. On that note, a micromachine is a large and complex system of interacting parts, with each component's properties affecting the overall assembly. With such a diverse range of components, the motor magnets likely play a small role for the entire life cycle of the whole machine. An LCA of the entire assembly could be used to calculate the environmental impact of whatever component is being processed on a given micromachine. This could strengthen the knowledge base, and help in decision-making.

4. Conclusion

To fully understand the impact of NdFeB magnets and components that incorporate them, clear and transparent input/output data would need to be gathered. Furthermore, as NdFeB magnets are being incorporated into new and existing technologies, their impacts will surely be investigated. Also, supplies of REEs will need to be examined, since there may be interruptions to the supply-chains. Given the complexity of REE extraction and processing, as new sources and methods are developed, their impacts must be investigated.

Another area that needs to be examined for NdFeB containing motors is what impacts may change when recycling is introduced. Recycling will add to the complexity of their life cycle, and may make NdFeB motors more desirable. Currently, recycling rates are low for REEs at present, but given the uncertainties in prices and possible supply shortages, this can certainly change. In closing, with a few substitutions NdFeB magnet motors will continue to be used in micromachines, and in countless other applications.

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