# Approaches to Efficiency and Life Cycle Assessment of Magnetic Bearing Systems

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**Abstract**

The scientific method for assessing a product system's impact on the environment is the Life Cycle Assessment. This work points out why the magnetic bearing community will benefit from embracing this method for the design of magnetically levitated systems. A brief introduction to LCA following the ISO14040 standard and an interpretation for the application to magnetic bearings is given. Links to popular databases, literature and software used in the field of LCA are equally provided. Due to the material similarity, some data from the field of electric motor LCA are given and the special role of rare earth permanent magnets is highlighted.

## 1 Motivation and Introduction

Global warming due to man-made climate changes and the environmental impacts of our industrial societies are very likely the biggest challenges of our time. Their importance stems from the large number of fields which are concerned, combined with the severity of the consequences if the challenges in the respective fields are not met. Significant hopes rest on technical improvement, striving for increased efficiency, reduced material usage, better reusability or recyclability, etc. In addition to their valuable inputs to increasing system lifetime, rotor speeds, or improved data harvesting and digitization opportunities, magnetic bearings can also contribute to these environmental goals.

The method for evaluating the related environmental aspects throughout the entire life cycle including raw material extraction, manufacturing, transportation, use, and the end of life in a cradle-to-grave or cradle-to-cradle approach is the life cycle assessment (LCA) which will be shortly described in Chapter 2. LCA serves as a key method in modern product design and helps to distinguish seemingly ecologically good design options from actually good ones.

Both, the international research community and, especially, the industrial players active in the field of magnetic bearings have got used to arguing the advantages of magnetic bearings through five typical points:

- Lubrication-free operation,
- friction-free and abrasion-free operation,
- long lifetime,

- hermetic sealing capacity and thus suitability for vacuum or cryogenic conditions, and
- suitability for high rotational speeds.

However, the energy and efficiency aspect of magnetic bearings is hardly discussed – with the exception of high speed systems where the absence of friction originates an efficiency advantage. A solid comparison of the overall environmental impact in the form of an LCA can help to establish a further strong point for the beneficial use of magnetic bearings in highly performant systems. This technique is, however, new to many researchers and the literature research at the beginning of the work for this paper yielded no example. Meanwhile, one single example of such a study was published in early 2021: In [1], Byrd et. al. have compared a magnetic bearing system to an oil lubricated bearing system in the application of large water cooled chillers.

It is, therefore, not the goal of this work to perform and present an LCA of a specific magnetic bearing. It is rather to bring the issue to the magnetic bearing community - the designers of these systems - and to present the related aspects in Chapter 3.

# 2 Life cycle assessment – a brief introduction

In the year 1995, the authors of the Nordic Council report on Guidelines on Life-Cycle Assessment [2] described the LCA as follows: "*The LCA methodology evaluates holistically the environmental consequences of a product system or activity, by quantifying the energy and materials used, the wastes released to the environment, and assessing the environmental impacts of those energy, materials and wastes.*" While the statement was clear and comprehensible, the mentioned "LCA methodology" was diverse. An increasing number of different implementation methods led the International Organization for Standardization to publish the ISO 14040 standard [3] in 1997 in its first edition in order to unify this methodology*. This unification of the different approaches defines the principles and structure of an LCA in order to achieve comparability between individual LCA results.

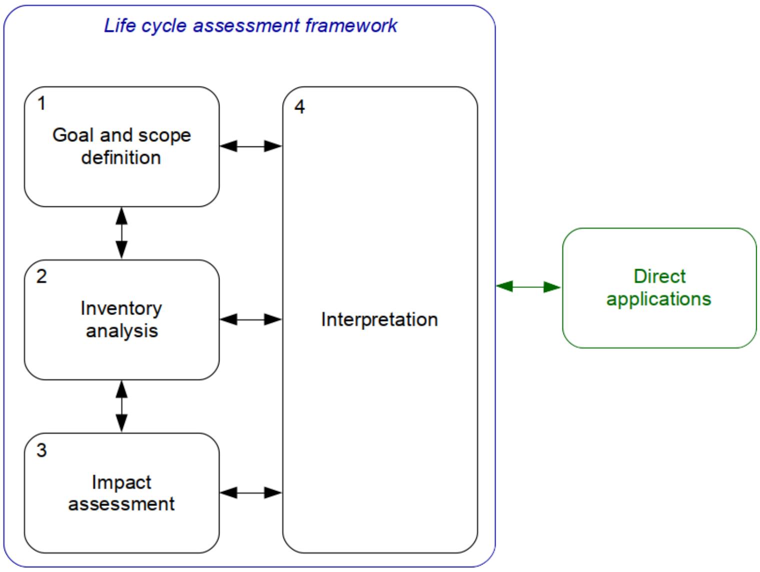

**Figure 1 Stages of a life cycle assessment according to ISO 14040:2006:1**

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* ISO 14044 [30] comprises directives and technical specifications added later.

The ISO 14040 standard defines four stages in an LCA. As it can be seen in Figure 1, the stages are interconnected and each stage influences every other stage in the LCA framework. Below, a short description explains the content of the individual stages. Many further guidelines and explanations for the application of ISO 14040 can be found in the literature, e.g. in [4] or [5].

### Goal and scope definition stage

The first task of an LCA study is to formulate its goal. Then the functional unit[†] as well as the system boundaries must be defined. Additionally, the handling of (missing) data has to be clarified and the required data quality has to be stated.

### Life Cycle Inventory (LCI) analysis stage

The inventory analysis deals with the description, acquisition, modelling and calculation of material and energy flows to create an inventory of input/output data. The numerical result contains only input flows from the natural environment und output flows to the natural environment. Materials and pre-products of the technical sphere have to be retraced to get the input streams from the ecosphere. The graphical result of the inventory is the process flow chart which visualizes the system boundaries and enables traceability.

The main part of an LCI analysis is the data acquisition. Data can either be measured, calculated, or estimated. Their accuracy influences the quality of the inventory considerably. With the mass and energy balance, the inventory can be validated. Unless every single process is balanced, the data quality is not sufficient.

### Life Cycle Impact Assessment (LCIA) stage

In the impact assessment stage, the data from the LCI analysis are bundled with regard to their potential environmental impacts in order to achieve a better understanding of the effects on the natural environment.

The goal is to assess all theoretical environmental impacts and to make them comparable. The combination of scientific-based assessment methods and subjectively generated compare mechanisms leads to an impact assessment consisting of mandatory and optional components.

While $CO_2$ emissions causing global warming are the most dominant environmental influence in today’s public perception, there are many different impact categories that may be considered in an LCIA. In fact, there is a wide range of LCIA *methods*, each defining a certain set of categories and characterization factors. Amongst the most popular methods are *ReCiPe* [6], *IPCC 2013*, *ILCD 2011* [7], *CML 2012* [8], and *Cumulative energy demand* [9] according to a recent survey [10]. A comprehensive description of the most popular method sets and the included impact categories has been published by Acero et al. in [11]. Table 2 shows typical impact categories present in many of the mentioned LCIA methods.

### Interpretation stage

In the fourth and last stage of the LCA study, the results of LCI analysis and the LCIA are compared with the goals defined in the first stage to generate conclusions, limitations, and recommendations. An important part is also the critical review, which is intended to ensure the validity of the study.

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[†] A functional unit is a quantified description of the function of a product that serves as the reference basis for all calculations regarding impact assessment.

| Impact category | Indicator unit |
|---|---|
| Climate change | kg CO2 equivalent |
| Stratospheric ozone depletion | kg CFC-11 equivalent |
| Ecotoxicity for aquatic fresh water | CTUe (comparative toxic unit for ecosystems) |
| Human Toxicity – cancer effects | CTUh (comparative toxic unit for humans) |
| Ionising radiation – human health effects | kg $U^{235}$ equivalent (to air) |
| Acidification | mol H+ equivalent |
| Eutrophication - aquatic | Fresh water: kg P equivalent<br>Marine: kg N equivalent |
| Land transformation | kg soil organic matter deficit |

**Table 1: Common LCIA impact categories [28]**

# 3 Application to Magnetic Bearings

## 3.1 Goal and Scope definition

This initial stage of an LCA is a highly individual task, depending on why an LCA shall be conducted. Typical tasks could be the comparison of one bearing technology to another one within a certain application as presented in [1] for a chiller compressor bearing system.

Furthermore, also the scope, i.e. the system boundaries have to be chosen. For a bearing system, the *physical boundary* may be drawn around the bearings alone, but more often, an assessment of a complete drive unit or even the entire process may be more meaningful.

The *life cycle boundary* can be selected according to the previously chosen goal. Focusing on raw material extraction and end of life may be sufficient for a purely material-oriented examination while additional inclusion of manufacturing, transportation, and use, would be necessary for an energy and emission investigation.

The defined goal and scope will later on determine the impact assessment perspectives and the final interpretation.

## 3.2 LCI analysis

### 3.2.1. Materials and manufacturing

The subsequent inventory analysis stage contains the most intuitive considerations for the magnetic bearing engineer confronted with an LCA: The assessment of the involved components for tracing their energy and material flows. Of course, this highly depends on the magnetic bearing topology. Figure 2 gives an exemplary collection of typical parts of an active magnetic bearing (AMB).

These components compare well to those of a permanent magnet synchronous machines (PMSM) electric machine: solid shaft parts, electric steel lamination, insulated copper wire, power electronic components, and rare-earth permanent magnets (REPM), i.e. NdFeB or SmCo type magnets, etc. These high energy density REPMs are also the predominant material aspect for an LCI of passive magnetic bearings (PMB) and will be given special consideration in Section 3.3.

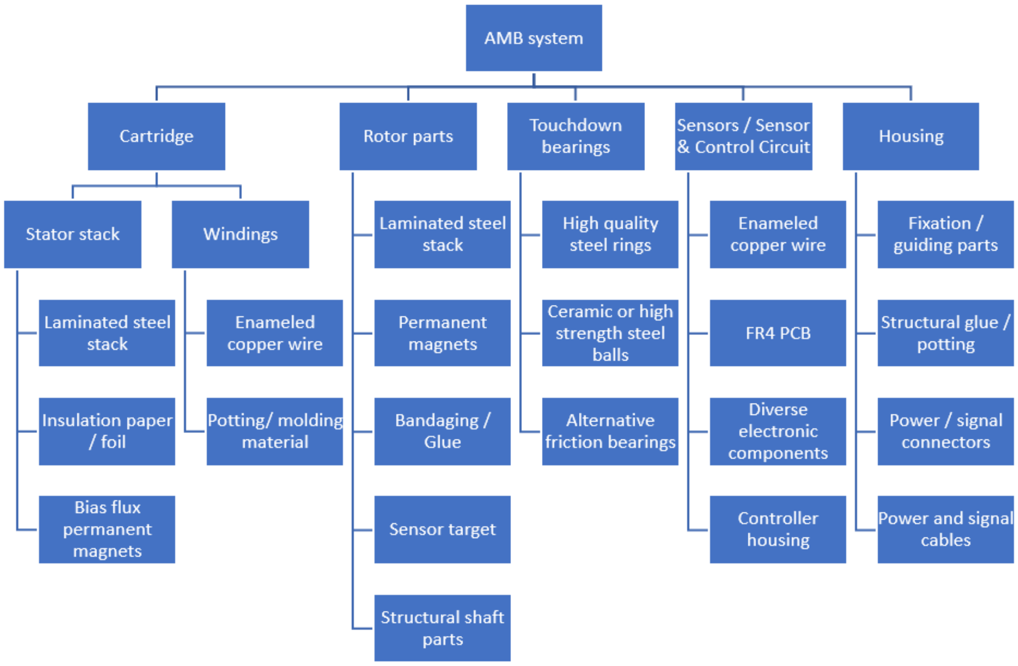

**Figure 2 Exemplary component structure of AMB system.**

Some recent publications have tracked the lifecycle issue for entire PMSMs [12], [13]. The authors of those two publications have presented a scalable LCI for automotive traction motors. Due to the mentioned material similarities between PMSMs and AMBs, the content gives valuable references for LCI magnetic bearing systems.

The next step after analyzing and listing the involved components is the energy and material flow, starting from raw material production to product assembly, i.e. a *cradle-to*-(factory) *gate*. **Figure 3** depicts such a flow diagram for PMSMs, demonstrating the impressive amount of aspects to consider.

### 3.2.2. LCI databases

Merging the component analysis and the material- and flow diagram allows to extract the masses of the required materials – not only of the finished magnetic bearing alone but of all process steps throughout its lifetime. For this step, the data on the necessary raw material and energy input per functional unit of a material are required. This information is typically found in LCI databases. A substantial number of such databases is offered online for free or under commercial license. A comprehensive list can be found at the openLCA Nexus [14], a short non-exhaustive selection according to the relevant topics may serve as orientation for magnetic bearing designers (information based on [14]):

- *ecoinvent* – Commercial database covering: agriculture, building and construction materials, chemicals, electricity, fishing, metals, refineries, textiles, tourism, transport, waste treatment and recycling, and water supply
- IDEMAT – Industrial Design & Engineering Materials database, also available as smartphone app giving low complexity information in form of eco-costs in € and carbon footprint in kg $CO_2$ equivalent

- Environmental Footprints (EF) – Partly free, partly commercial database offered by the European Commission covering amongst others: agriculture and foods, textile, thermal insulation, metal sheets, copper production, paints, IT equipment, photovoltaic electricity production
- NEEDS - New Energy Externalities Developments for Sustainability focusing on future electricity supply systems, material supply, transport services

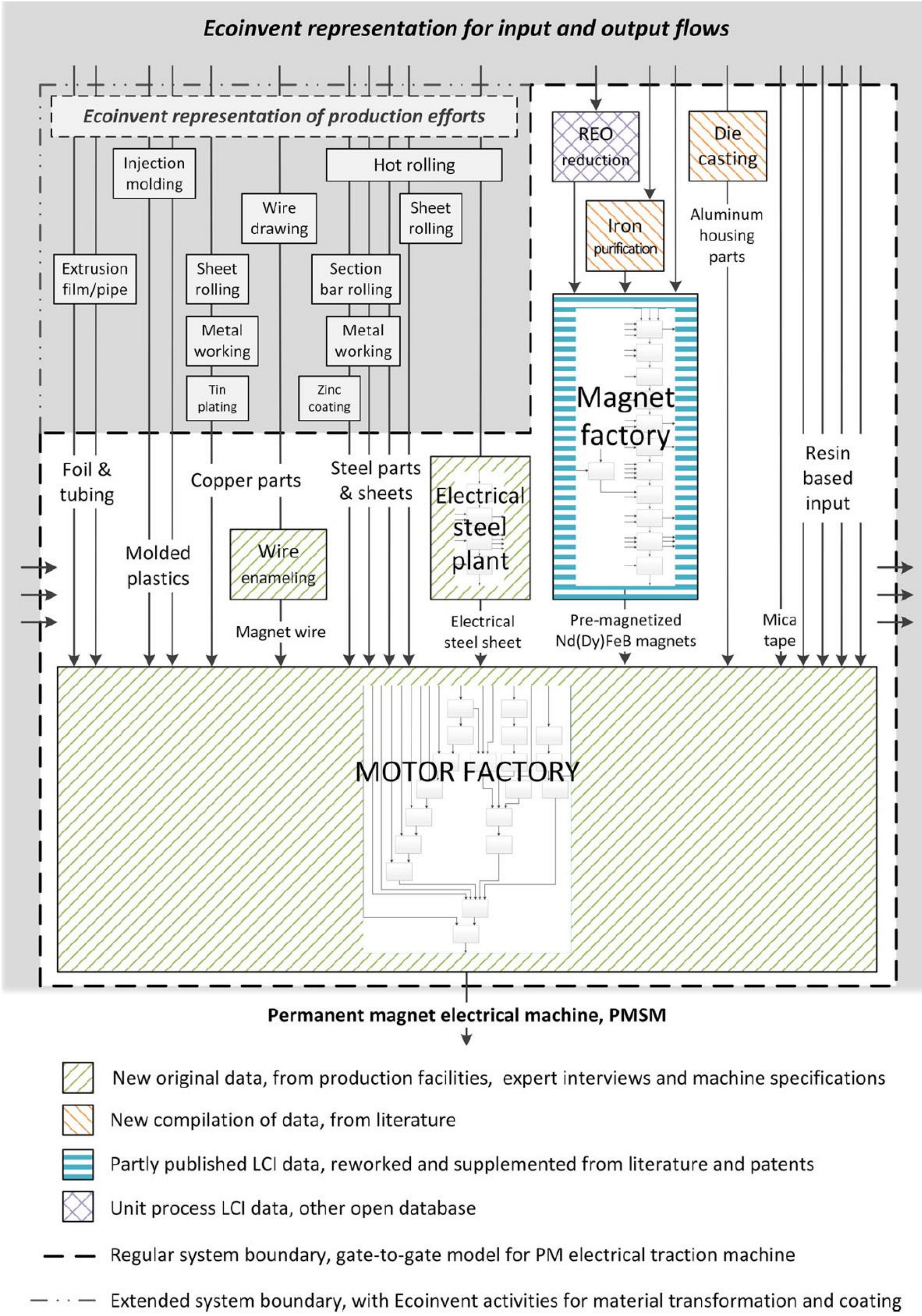

**Figure 3 Flow diagram of material and energy for PMSM components presented in [13]**

In order to demonstrate the granularity appropriate LCIs, Table 2, Table 3, and Table 4 present the LCI for NdFeB REPM, silicon steel sheets, and enameled copper. It has to be stressed that the mentioned electricity input and raw materials only cover the described processes – large shares are included in the raw products e.g. the unalloyed steel or the uncoated copper wire. This dependencies are resolved when evaluating the LCA in suitable software tools (such as openLCA [15], GaBi [16], or SimaPro [17], etc.).

| **Production of 1 kg of NdFeB nickel coated REPM** | | |
|---|---|---|
| **Process Input** | Amount | Unit |
| Unalloyed steel for electrolytic iron | 913 | g |
| Electricity, iron electrolysis | 2 | kWh |
| Boron carbide | 15 | g |
| Neodymium | 310 | g |
| Nickel | 11 | g |
| Dysprosium | 91 | g |
| Electricity, sintering | 8.4 | kWh |
| Electricity, other | 5.6 | kWh |
| Hydrogen | 0.6 | kg |
| Caustic soda | 1 | g |
| Sulfuric acid | 1.4 | g |
| Water | 6 | kg |
| **Emissions to air** | Amount | Unit |
| Nickel | 4.2 | mg |
| **Emissions to water** | Amount | Unit |
| Nickel sulfamate (23% nickel) | 5.1 | mg |
| **Solid waste** | Amount | Unit |
| NdFeB scrap | 200 | g |
| Sludge (ferrous chloride) | 250 | g |
| Sludge (97% nickel sulfamate, 3% nickel chloride, 24% nickel in total) | 2.2 | g |

**Table 2: Process inputs, emissions, and wastes of NdFeB REPM, data retrieved from [13]**

| **Enameling of 1 kg of copper wire** | | |
|---|---|---|
| **Process Input** | Amount | Unit |
| Copper wire, uncoated | 0.96 | kg |
| Liquid enamel, polyester share | 43 | g |
| Liquid enamel, xylene solvent share | 23 | g |
| Electricity, enameling | 0.5 | kWh |
| **Emissions to air** | Amount | Unit |
| Xylene | 23 | g |

**Table 3: Process inputs, emissions, and wastes of enameling copper wire, data retrieved from [13]**

| Production of 1 kg of electrical silicon steel sheets | | |
|---|---|---|
| **Process Input** | Amount | Unit |
| Unalloyed steel | 1.116 | kg |
| Ferrosilicon | 31 | g |
| Aluminum | 5 | g |
| Electricity (starting from alloyed steel) | 0.63 | kWh |
| Propane / LPG | 12 | g |
| Sulfuric acid | 19 | g |
| Rolling / lubricating oil | 0.4 | g |
| Quicklime powder | 0.8 | g |
| Phenolic resin | 1 | g |
| **Emissions to air** | Amount | Unit |
| $CO_2$ | 36 | g |
| Nitrogen oxides | 0.1 | g |
| Sulfur oxides | 0.06 | mg |
| **Solid waste** | Amount | Unit |
| Steel scrap | 114 | g |
| Sludge (60% $CaSO_4$, 40% $Fe(OH)_2$) | 3.3 | g |

**Table 4: Process inputs, emissions, and wastes of electrical steel sheet, data retrieved from [13]**

### 3.2.1. End of life

In the end of life consideration, the used materials will contribute either to the waste fraction or, in case of reuse or recycling, to the emission sum through negative emission factors. Table 5 gives values for end of life greenhouse gas emission values for the different scenarios.

| **Material** | Reuse emissions | Recycle emissions | Landfill emissions | Unit |
|---|---|---|---|---|
| Steel | -3.58 | -1.81 | 0.01 | kg $CO_2$ / kg |
| Aluminum | -15.33 | -7.19 | 0.72 | kg $CO_2$ / kg |
| Copper | -7.48 | -4.71 | 0.01 | kg $CO_2$ / kg |

**Table 5: Emission factors of reuse, recycling, or landfill scenario of selected materials from [1].**

### 3.2.2. Use phase energy

Magnetic bearings do not require any operation medium other than electric energy. Due to their contact-free operation, there is no need for lubrication, i.e. no need for operating fluids that have to be exchanged in certain intervals, that would have to be filtered, cooled, or in some other way conditioned. The same is true for wastes; Ideal magnetic bearings do not produce any wastes during operation – neither gaseous, fluid nor solid. As the only exclusion, abrasion from touchdown bearings may be considered, especially if low-cost friction type bearings are used.

This absence of operation media and use phase wastes reduces the material and energy flows in production and operation which is reflected in the LCI.

The actual magnetic bearing energy consumption is primarily dominated by parasitic losses such as windage losses or eddy current losses. The structural and material measures for mitigating these losses are well understood and frequently described in the literature. Also the control of AMBs has significant influence on the power consumption and a number of measures can be applied in order to reduce the mean input power, e.g. disturbance rejection through notch filters [18], zero-force control achieved by offsetting the axis of rotation against the direction of gravity or a (quasi) constant process force [19], or by applying bias magnets in the form of passive lift bearings or compensation bearings [20] [21].

### Chiller compressor example

The biggest and most important efficiency aspect stems from an intrinsic capacity of magnetic bearings: the friction-less operation. In addition to the absence of mechanical bearing losses, this also permits higher speeds at which radial compressors reach higher efficiency levels and driving motors can be built more compact and thus, with less material input. Adding to the energy savings for not having to condition the lubrication oil, these advantages give the magnetically levitated chiller compressor described in [1] an astonishing 38.8% advantage in consumed use energy over the comparison compressor with oil bearings. This amounts to a mean input power reduction of 54.5kW.

### Power plant turbine example

Another impressive example has been published in [22] by Grund et al. In 2014, Siemens has installed the world's first magnetically levitated power plant turbine (see Figure 4) in the lignite-fueled plant of Jänschwalde, Germany. Its 2.5 ton rotor is levitated by 2 radial AMBs and an axial AMB. The magnetic bearings have been recognized to increase the turbine efficiency by 1%. A large contribution to that increase, however, does not come from advanced bearing efficiency but stems from the fact that the lubrication oil conditioning including filtering, preheating, etc. can be completely eliminated from the system.

Ironically yet reasonably, it needs to be said that the complete lignite power plant will be shut down until 2028 in order to reduce carbon emissions.

**Figure 4 10MW feedwater pump on AMB installed in a fossile fuel power plant. Image: courtesy of Siemens (Turbinenwerk Görlitz)**

### High-purity pump and spin processor example

The process steps in wafer fabrication involve multiple pumping of liquids into or out of the process chamber. Since any contamination must be prevented, perfect sealing of the pumps involved is required. Magnetically levitated pumps allow hermetic separation of rotor and stator. Originally used mainly in the chemical mechanical planarization (CMP) process for pumping slurry and as blood pumps in medical technology, these pumps (Figure 5, left image) are increasingly being used in the semiconductor, medical and pharmaceutical industries.

Another field of AMB application are so-called spin processors (Figure 5, right image), i.e. drives which rotate the wafer to distribute photoresist or to spin off cleaning liquids in a process chamber conditioned by vacuum or process gas filling. Due to the hermetic separation of rotor and stator by the process chamber wall, the spin process can be performed in the closed atmosphere, which reduces impurities and saves time and energy by eliminating the conditioning process.

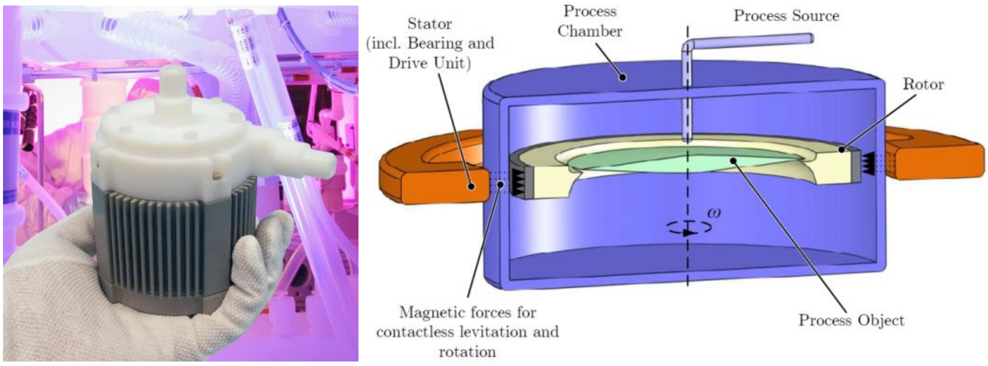

**Figure 5 High-purity pump (left) and spin processor model (right) [29]**

Both mentioned systems alone may be disadvantages in terms of life cycle impact when directly compared to pumps and spin processors with conventional ball bearings. However, due to their high-purity operation, an increased chip yield, reduced processing time, or significantly reduced process gas consumption may be achieved. The authors of this article do not dispose of concrete data on these aspects, it is, however, highly likely, that a significantly larger system boundary definition would be necessary when comparing such complex systems. Additional filters, external purification systems, complex sealing systems, and the longer plant operation time due to lower chip yield of the compared conventional bearing solution would also have to be considered. In that case, the life cycle impact of the magnetically levitated systems will very likely outperform the conventional solution.

## 3.3 LCIA

According to the selected LCIA method (cf. LCIA methods, Section 2), the LCIA will express the material and energy flow of the LCI in the respective set of impact categories. This evaluation is typically provided by an LCA software tool in combination with appropriate LCI databases.

Regardless of the precision of the data provided in a database, there are certain dependencies of the impact values, e.g. to the geographic location selected in the scope of the LCA. The biggest geographic influence on magnetic bearing systems originates from the carbon intensity of the electric energy at the place of operation. Values differ from >600 g CO2 equivalent / kWh in coal-intensive regions to <100 g CO2 equivalent / kWh in regions which exploit wind and hydro power. This of course can heavily influence the LCIA result concerning global warming potential.

Also REPM materials play a particular role for some selected impact categories. They constitute a central element of both, AMBs with PM bias flux and PMBs, and their environmental impact is widely discussed in the general public. Especially the human toxicity and ecotoxicity aspects make the use of REPM very critical.

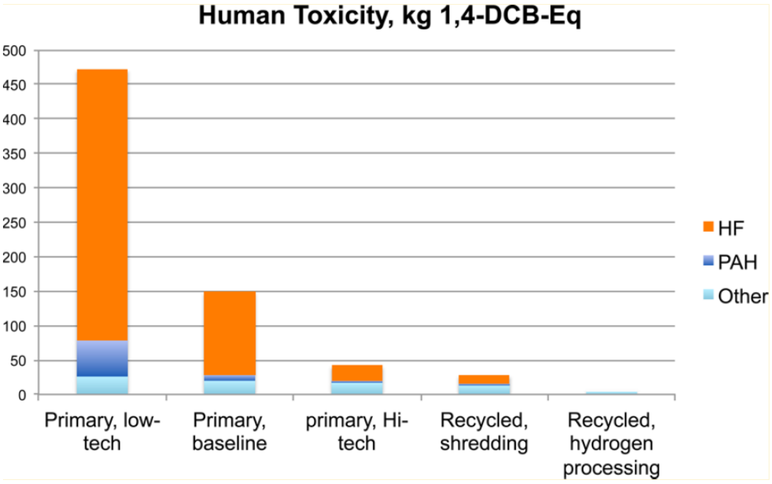

**Figure 6 Comparison of human toxicity of different REPM production routes presented in [23]. (HF: hydrogen fluoride, PAH: polycyclic aromatic hydrocarbons)**

Therefore, numerous recent projects and publications deal with the LCA of REPM ( [23], [24]) and with the comparison between magnet production from virgin, “primary” raw material and production from recycled magnet material [25].

In Figure 6, the authors of [25] show the potential of REPM recycling and the possible hazards of low-tech REPM primary production. This is a clear reminder to use REPM materials only where they can contribute a real benefit in terms of an LCIA and to avoid distributing them for price reasons only to household or other consumer products which will end up in landfills and incinerators.

## 3.4 Interpretation

As with the Goal and Scope definition stage, the interpretation is a highly individual task, depending on the defined goal, the used LCIA method and the overall purpose of the conducted LCA. Therefore, this stage shall not be further considered in this work.

# 4 Conclusion and Outlook

LCA has become a buzzword in today’s efforts to drive technical development for combatting detrimental environmental impacts. A large community of researchers has been dealing with the environmental impact assessment for the past 30 years. There are countless publications, standards, databases, software suits, methods, etc. around this topic.

Nevertheless, only during the work on this article, the first scientific publication on an LCA for a magnetic bearing system was published, showing how little this important topic has been perceived by the magnetic bearing community.

Despite the fact that many aspects of an LCA for a magnetic bearing system can be translated from LCAs for electric motors due to similarity of the used raw materials and manufacturing processes, significant effort has still to be made to establish widely-accepted, comparable, and potentially scalable models for the most dominant types such as radial and axial AMBs.

Regardless of these difficulties ahead, the authors of this article hope to have presented a first insight into LCA from and for the viewpoint of a magnetic bearing designer. The merits of embracing this methodology into the workflows of magnetic bearing design are high:

The analyses of [1] and [22] have shown, that the overwhelming advantage of the magnetically levitated compressor or turbine systems lies in the better system efficiency in combination with long on-times, i.e. in the consumed electrical use energy.
The same conclusion is drawn by Auer and Meincke in [26] who assessed induction machines with efficiency classes IE2, IE3, and IE4 and by Rothboeck in [27] when analyzing ferrite-type and NdFeB-type PMSM in different use case scenarios. It is, therefore, very clear, that in addition to the five classical arguments for magnetic bearing systems, an efficiency advantage will materialize in better LCA performance in systems with long lifetime and long on-time. At the same time, a clear LCA result will also help to identify the fields where magnetic bearings will not be beneficial.

The given examples have worked on high power systems but the future may also bring examples for much smaller systems in industrial production machines, public or building infrastructure or the HVAC sector as all of these fields dispose of machines with long on-times.

A less evident but potentially even more rewarding field lies in applications where magnetic bearings enable new solutions or processes due to their special features (e.g. lubrication-free, hermetic, cryogenic operation capability). When conducting an LCA for system comparison, the conventional reference solution may dispose of significantly more system parts to achieve the same performance as the magnetically levitated one. Depending on the application, the environmental impact can differ not only by a few percentage points, but by whole orders of magnitude.

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