Available online at www.sciencedirect.com
ScienceDirect
journal homepage: www.elsevier.com/locate/ijrefrig

Magnetic vs. vapor-compression household refrigerators: A preliminary comparative life cycle assessment

Behzad Monfared [a,*], *Richard Furberg* [b], *Björn Palm* [a]

[a] *Department of Energy Technology, Division of Applied Thermodynamics and Refrigeration, Royal Institute of Technology, Brinellvägen 68, SE-100 44 Stockholm, Sweden*
[b] *Electrolux AB, Sankt Göransgatan 143, 11238 Stockholm, Sweden*

ARTICLE INFO

Article history:
Received 29 August 2013
Received in revised form
18 February 2014
Accepted 26 February 2014
Available online 7 March 2014

Keywords:
Magnetic
Refrigeration
Life cycle assessment
Environment

ABSTRACT

This paper seeks to shed light on the question whether a magnetic household refrigerator with permanent magnets is more environmentally friendly than a conventional, vapor-compression refrigerator. Life cycle assessment has been used as a tool to investigate the environmental impacts associated with the life cycle of a magnetic refrigerator. The results of the assessment have been compared with those of a conventional, vapor-compression refrigerator with the same functionality. The comparison reveals that the magnetic refrigeration has higher environmental impacts mainly due to the use of rare-earth metals used in the magnet material. The possibility of compensating for this shortcoming through reuse of the magnetic materials or improving the design and efficiency of the magnetic refrigerator has been examined. In addition, the effect of the electricity mix consumed during the use phase, as one of the key factors determining the life cycle environmental impacts, has been investigated.

Réfrigérateurs domestiques magnétiques et à compression de vapeur comparés : Evaluation comparative préliminaire en termes de cycle de vie

Mots clés : Magnétique ; Réfrigération ; Evaluation en termes de cycle de vie ; Environnement

1. Introduction

Recently, there has been growing interest in research on magnetic refrigeration at room temperature as an alternative to the conventional vapor-compression technology. Many researchers have seen magnetic refrigeration as a potentially more efficient and more environmentally-friendly technology than vapor-compression technology. More specifically, some

* *Corresponding author*. Tel.: +46 8 790 74 50; fax: +46 8 20 41 61.
E-mail address: behzadam@kth.se (B. Monfared).
http://dx.doi.org/10.1016/j.ijrefrig.2014.02.013

Nomenclature

1,4-DB	1,4 dichlorobenzene
B_0	magnetic field in high-field region [T]
B	Boron
CFC-11	trichlorofluoromethane
CO_2	carbon dioxide
eq	equivalent
Fe	iron
m2a	square meter times year
Mn	manganese
NMVOC	non methane volatile organic carbon compound
PM10	fine particulate matter with a diameter of less than 10 μm
T_{amb}	ambient temperature [K]
T_c	cabinet temperature [K]
N	nitrogen
Nd	neodymium
P	phosphorus
Q_c	cooling power [W]
U235	uranium-235
V_{MCM}	volume of the magnetocaloric material [m^3]
Si	silicon
SO_2	sulfur dioxide
μ	exergetic cooling power per unit volume of magnetocaloric material and unit magnetic field [$W\ T^{-1}\ m^{-3}$]

publications mention global warming potential (GWP) and ozone depletion potential (ODP) of zero as an advantage of magnetocaloric materials over the gaseous refrigerants of conventional systems (Aprea et al., 2011; Engelbrecht et al., 2006, 2011; Gschneidner and Pecharsky, 2008; Kitanovski et al., 2008; Muller et al., 2007; Pecharsky and Gschneidner, 1999; Yu et al., 2010). Apart from such brief comments, little can be found in the literature regarding the environmental impacts in different stages of the life cycle of an application of magnetic refrigeration. A comprehensive study of the whole life cycle of a magnetic refrigeration device and a vapor-compression device is, therefore, needed to determine whether a magnetic refrigerator is a more environmentally-friendly choice than a conventional refrigerator.

This paper reports a life cycle assessment (LCA) made to investigate the environmental impacts of the whole life cycle of a small, magnetic, household refrigerator with permanent magnets. In this study, the life cycle environmental impacts of the magnetic refrigerator are also compared to that of a similar vapor-compression refrigerator with the same functionality. The comparison is made to see how environmentally-friendly a magnetic refrigerator will be (if it succeed to enter the market) assuming it being as efficient as a similar conventional refrigerator. As the capacity per unit mass of vapor-compression compressors has improved over time (see Fig. 1), it is expected that less amount of magnetic materials can provide the needed cooling power as the magnetic refrigeration technology develops. Similar improvements in efficiency and material recovery rates in end of life of

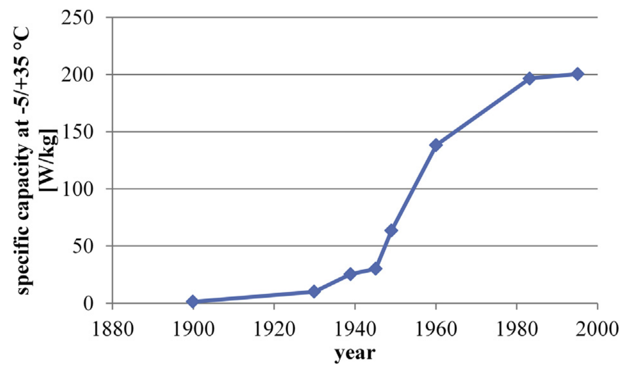

Fig. 1 – Increased capacity per unit mass of compressors in the last century (the latest three examples are hermetic motor-compressor) (Granryd et al., 2011).

the magnetic refrigerators are also imaginable. Therefore, the potential improvements in magnetic refrigeration technology have been considered when comparing it with conventional refrigeration, which is already a mature technology.

Although a well-defined, specific unit has been the subject of this study according to the requirements of LCA methodology, with some care and caution, one may use the qualitative results for more general conclusions. Determining the potential life-cycle environmental impacts of room temperature magnetic refrigeration can be helpful in evaluating the opportunities and threats involved in developing this new technology.

2. Method and assumptions

For the purpose of the study an attributional, comparative life cycle assessment (LCA) has been done. The environmental impacts of the whole life cycles (production, use phase, and end of life) of both conventional and magnetic refrigerators are estimated and compared. The system boundary, indicating which processes are included in the assessment, is shown in Fig. 2; less significant processes are not shown in the diagram.

The basis of the individual assessment and the comparison between the two refrigerators is the functionality of the refrigerator: cooling in exchange for electricity consumption. The functional unit in this study is one household refrigerator, either vapor-compression or magnetic, with the following specifications: energy efficiency class of A+++; annual energy consumption of 66.17 kWh; subtropical (ST) climate class (18–38 °C ambient temperature); refrigeration compartment volume of 223 L; no freezer compartment; gross volume of 230 L; free-standing (not integrated); one-door; lifetime of 14 years.

For a household refrigerator with the specifications listed as the functional unit, the required maximum cooling power is estimated to be 46 W to keep cabinet temperature of 4 °C at the ambient temperature of 38 °C, satisfying the requirements for subtropical climate class. However, the refrigerator does not work under the extreme conditions throughout its lifetime. The assumption that the conventional and magnetic

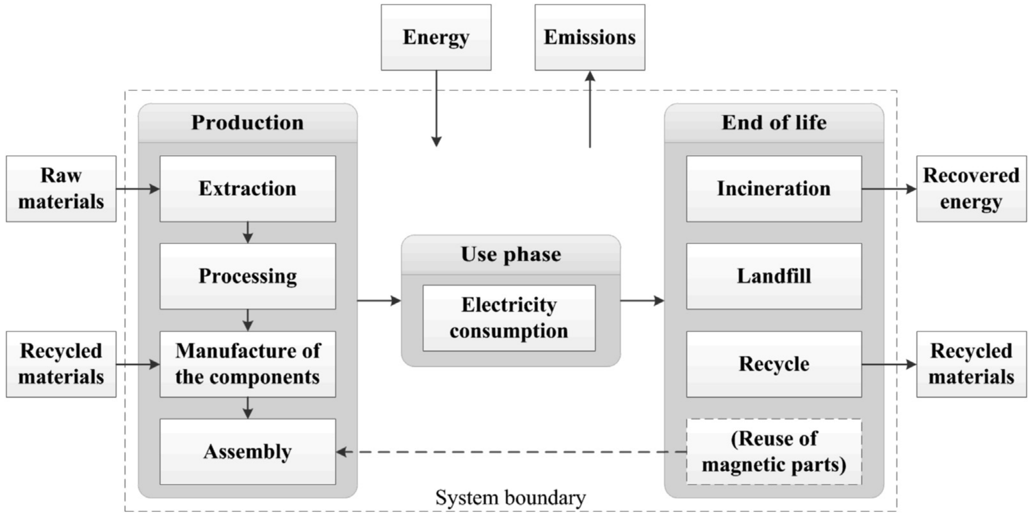

Fig. 2 – The inputs, outputs, and the main processes of the modeled system.

refrigerators studied in this project have exactly the same functionality implies that both refrigerators have the same cooling power and electric power consumption.

The software tool used for doing the LCA is SimaPro 7.3.3 product of PRé Consultants bv. The data for life cycle inventory analysis are mainly taken from ecoinvent database v2.2 and European Life Cycle Database (ELCD) v2.0, as implemented in Simapro 7.3.3. The environmental loads determined by the life cycle inventory analysis are converted to 18 mid-point environmental impacts using the impact assessment method of ReCiPe with Hierarchist perspective (Goedkoop et al., 2013).

The impact categories included in the selected impact assessment method are climate change, ozone depletion, human toxicity, photochemical oxidant formation, particulate matter formation, ionizing radiation, terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial eco-toxicity, freshwater eco-toxicity, marine eco-toxicity, agricultural land occupation, urban land occupation, natural land transformation, water depletion, metal depletion, and fossil depletion (Goedkoop et al., 2013). The relative importance of these impacts can be discussed or they can be quantitatively weighted in different ways, which is beyond the scope of this study. However, to keep the article short and concise, climate change (with the unit equivalent kg CO_2), as one of the mostly debated environmental impacts in refrigeration field, has been chosen as a representative of the rest of the impact categories to show some of the results.

In this assessment, it is assumed that the production stage, use phase, and the end of life of refrigerators are all in Europe and not far from each other; this assumption affects the choice of material market, energy sources, and the transportation means/distances. The electricity mix used to model manufacture of the components, assembly, use phase, and end of life is the medium voltage or low voltage electricity derived from “Electricity, production mix RER/RER U” taken from ecoinvent database v2.2, as implemented in SimaPro 7.3.3.

The life cycle model of the conventional refrigerator has been based on the data available in “Preparatory Studies for Eco-Design” for “Domestic Refrigerators & Freezers” (Faberi, 2007). The conventional refrigerator has a hermetic motor-compressor with isobutane (R600a) as refrigerant.

The machines currently built cannot be good representatives for magnetic refrigerators since they are not produced commercially and the technology is still developing. Therefore, the available information about conventional refrigerators is used as a basis for modeling the magnetic refrigerators, but some materials and processes which are not common between the conventional and magnetic refrigerators are replaced by the processes and materials exclusively used in magnetic refrigerators. Care has been taken that by replacing some parts of the model the function of the refrigerator remains unaffected.

It is assumed that the body of the refrigerator, the control equipment, and the heat exchangers are the same for both refrigerators. However, the hermetic motor-compressor, refrigerant (R600a), expansion device, and compressor oil do

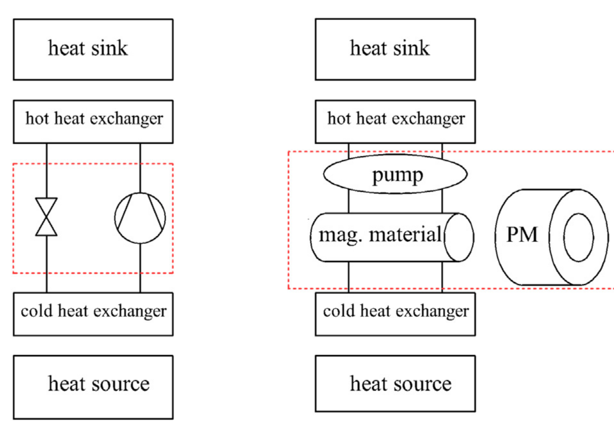

Fig. 3 – Schematic models of (left) conventional refrigerator and (right) magnetic refrigerator.

not exist in the magnetic refrigerator and are replaced by the magnetocaloric material, the permanent magnet, pump, motor, and water. In other words, the magnetic refrigerator is modeled by removing the parts inside the red box from the conventional refrigerator (Fig. 3, left) and adding new parts shown in the red box in Fig. 3, right.

For the magnetic refrigerator, manganese-iron-phosphorus-silicon (MnFePSi) compound as the magnetocaloric material and neodymium-iron-boron (NdFeB) permanent magnet have been chosen. It should be noted that, the data regarding some of the processes involved in manufacturing MnFePSi and NdFeB have not been available to us; furthermore, not all the materials and processes can be found in the LCA databases. Therefore, to compensate for the lack of data, theoretical estimations and reasonable assumptions have been inevitable: the processes described by Campbell (1994) and Thanh et al. (2008) are used to model the magnetic materials; stoichiometric ratios of $MnFeP_{0.5}Si_{0.5}$ are used to calculate mass of elements; red phosphorus is approximated by white phosphorus; apart from Si, modeled as high purity material, the elements used in the model have the purity suitable for ordinary applications; converting boron oxide to boron is approximated by converting aluminum oxide to aluminum; small amounts of praseodymium, dysprosium, and terbium, which may be used in magnet, is approximated by neodymium; material losses during manufacture are not modeled; ball milling energy consumption is estimated using Bond's equation; sintering and annealing energy consumptions are calculated based on the energy consumption of commercially available devices; cool down to room temperature after annealing is assumed to be environmentally neutral. To use materials with less purity needed for magnetic materials in the model underestimates the environmental impacts of their manufacture; nevertheless, the simplification does not change the conclusions made.

Estimation of the needed mass of the magnetocaloric material and the permanent magnet is rather uncertain since magnetic refrigeration at room temperature is not a mature technology and no magnetic refrigerator prototype has been reported in the open literature with the cooling power and the temperature span corresponding to the specifications of the functional unit of this assessment. In this study the mass of magnetocaloric material (MnFePSi) is estimated based on the metric μ defined by Arnold et al. (2011) as

$$\mu = \frac{Q_C\left(\frac{T_{amb}}{T_C} - 1\right)}{B_0 V_{MCM}} \tag{1}$$

where Q_c is cooling power [W]; T_{amb} is ambient temperature [K]; T_c is cabinet temperature [K]; B_0 is magnetic field in high-field region [T]; V_{MCM} is volume of the magnetocaloric material [m^3]. For the cooling power and temperature span ($T_{amb} - T_c$) of interest, the value chosen for μ in this study is 1×10^5 W T^{-1} m^{-3}, which seems realistic according to the values reported so far in the open literature. The volume of magnetocaloric material given by Eq. (1) for magnetic field of 1.4 T is 4×10^{-5} m^3 (0.2 kg).

The needed volume of magnet material is influenced by different design parameters such as number of beds in which the magnetocaloric material is distributed, number of the high field regions, and design of magnet assemblies. It is, therefore,

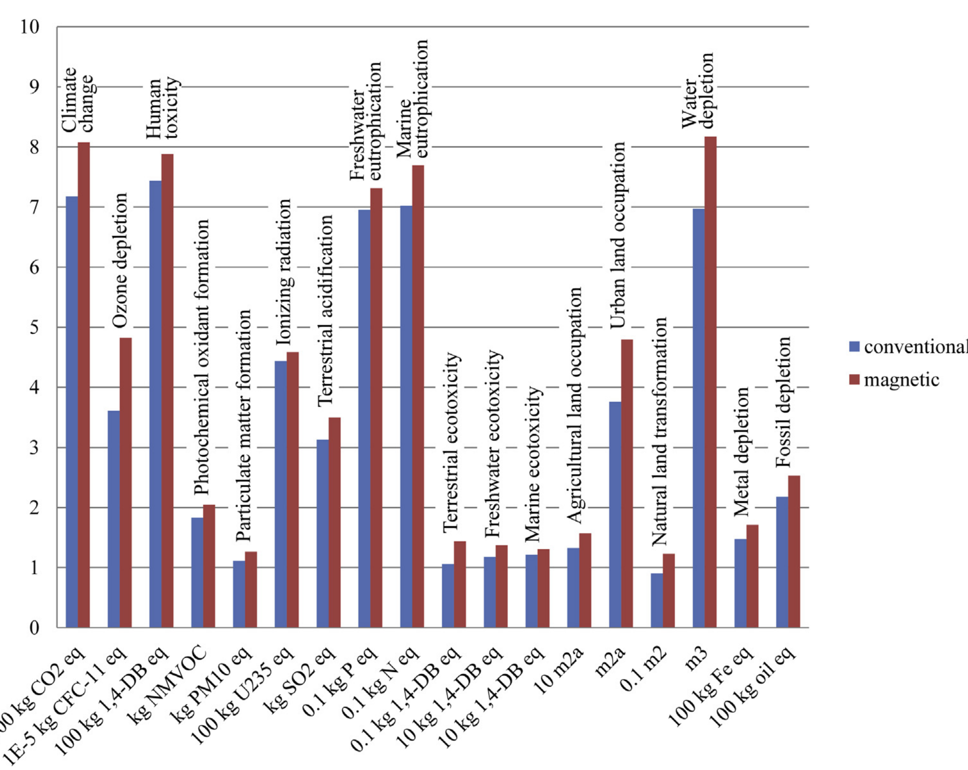

Fig. 4 – The environmental impacts of conventional and magnetic refrigerators (the horizontal axis shows the unit for each impact category).

not easy to determine the magnet volume with certainty in this study. However, considering the values reported in the literature, e.g. by Bjørk et al. (2010) and Yu et al. (2010), the volume of the magnet is assumed to be 6.4×10^{-4} m^3 (4.76 kg). Such an assumption is closer to designs with economical use of magnetic materials. To make up for the uncertainty in the estimated volume of the magnetic materials and to consider the probable advancements in the technology, the assessment has been repeated for higher μ-values, assuming that mass of the magnetocaloric material and permanent magnet vary linearly with inverse of μ.

In case of the conventional refrigerator, according to Faberi (2007), 85% of the plastic parts and 95% of the metal, glass, etc. parts are recycled. 10% of the plastic parts are incinerated, and the remaining materials (5% of each) are landfilled. For the magnetic refrigerator, 100% landfill of the magnetic materials is assumed, which reflects the current actual end of life of such materials (Du and Graedel, 2011). However, there are ongoing works to study the possibilities and challenges of recycling magnetic materials. Among the activities in this field, those of the European rare earths resource efficiency and recycling working group, consisting of technical experts, business leaders, and policymakers, as a part of European Rare Earths Competency Network can be mentioned. Schüler et al. (2011) have reviewed the proposed technologies and challenges to improve the current situation of recycling rare-earth materials and proposed a plan for implementing recycling. Considering the potential in recovery of magnetic materials, 90% reuse of magnetic materials has also been investigated in this study. Since separating the rare-earth metals from alloys to recycle them is energy intensive and complex, reuse of magnetic materials, as an easier solution, has been considered in this study (Schüler et al., 2011). The method of "approximation with closed loop recycling" has been used to allocate the environmental burdens of producing and disposal of the reused materials (Baumann and Tillman, 2004). For the rest of the materials, the percentages used for conventional refrigerator are applicable for the magnetic refrigerator.

3. Results

To have a general overview, the assessment results for the conventional refrigerator and the magnetic refrigerator are presented in Fig. 4. As can be observed, the magnetic refrigerator has larger environmental impacts in all categories.

As summarized in Table 1, the most significant impact on climate change is related to the use phase (electricity consumption) of the refrigerators. The same observation can be made for the rest of the impacts, apart from human toxicity and metal depletion for both refrigerators and urban land occupation for magnetic refrigerator where the production phase has larger share.

It must be noted that the life cycle environmental impacts can dramatically change if a different electricity mix is used during the use phase. For instance, if the refrigerators consume solely the NORDEL electricity mix (electricity production of Sweden, Norway, Finland and Denmark), the amount of emissions and the contribution of the life cycle stages in the total emissions will be considerably different. According to Table 2, the contribution of production stage to climate change impact can be more or equally high compared to that of the use phase with NORDEL electricity mix. In most of the other impact categories, production stage has the largest share for both refrigerators.

Table 1 – Share of the main life cycle stages from the total climate change impact of each refrigerator.

	Production	Use phase	End of life	Total (kg CO_2 eq)
Magnetic refrigerator	33%	65%	2%	808
Conventional refrigerator	25%	73%	2%	718

According to Table 1, the end-of-life processes have a quite small share in the climate change impact of both refrigerators (similar to the rest of the impact categories). In addition, the use phase is the same for the conventional and magnetic refrigerator in this study. Therefore, the higher environmental impacts of the magnetic refrigerator (Fig. 4) is related to the magnetic materials which are absent in the production stage of the life cycle model of the conventional refrigerator. More detailed analysis of the life cycle of the magnetic refrigerator reveals that the rare-earth magnet, NdFeB, has a major contribution to most of the environmental impacts of the production stage. For instance, about 30% of the climate change impact associated with production stage is related to the NdFeB magnet. The environmental loads of the NdFeB magnet are mainly due to the activities from mining to production of neodymium oxide. Since no rare-earth metal is used in the magnetocaloric material, MnFePSi, and its mass is relatively low, it does not add such remarkably high environmental loads to the production stage.

Although the rare-earth materials are expensive and their extraction imposes large loads on the environment, more than 99% of the rare-earth metals go to landfills (Du and Graedel, 2011). A sensitivity analysis can reveal how a more environmentally friendly waste scenario can reduce the overall impacts of the magnetic refrigerator. In the alternative waste management scenario it is assumed that the magnetic materials are removed from the refrigerator before shredding it in a hammer mill to be used in a new refrigerator. The reuse rate assumed in this scenario is 90%. Considering reuse of magnetic materials implies that the materials are assumed to remain competent after the first use. The results for reusing the magnetic materials once, twice, and six times, as an

Table 2 – Life cycle climate change impact of the refrigerators consuming NORDEL electricity mix during the use phase.

	Production	Use phase	End of life	Total (kg CO_2 eq)
Magnetic refrigerator	59%	38%	3%	464
Conventional refrigerator	48%	48%	4%	374

extreme which corresponds to almost a century for 14-years lifetime, are presented in Fig. 5. As mentioned earlier, suggested processes for recycling of magnetic materials by separating the elements from alloys involves energy intensive, complex processes investigation of which is not within the scope of this study.

The environmental impacts of the magnetic refrigerator will also be lowered if the needed amount of magnetic materials is reduced through improving the design. The results of increasing μ-value by the factors 4 and 10 are shown in Fig. 5. Applying 4-times higher μ-value to the model has reduced the environmental impacts virtually as effectively as reusing magnetic materials six times. With further increase in μ-value the environmental impacts can approach those of the conventional refrigerator as Fig. 5 for 10-times higher μ-value suggests. It is noteworthy that technical limitations may not allow very high μ-values. Combining 90% reuse scenario with higher μ-values gives even better results presented in Fig. 6.

As mentioned, the electricity consumption during the use phase of the refrigerators is the most critical process in the life cycle. Another way to reduce the environmental impacts of the magnetic refrigeration is through reducing its electric power consumption by increasing its efficiency. In this paper, the efficiency is defined as the ratio of the Carnot cycle work to the actual electricity consumption of the refrigerator. It should be noted that decreased annual energy consumption through increasing the efficiency means that the refrigerator does not have the same functional unit, based on which the rest of the results have been obtained. By increasing the efficiency of the magnetic refrigerator by 4% its ionizing radiation impact reaches that of the conventional refrigerator, while the rest of the impacts are still higher than that of the conventional refrigerator (Fig. 7). However, not all the environmental impacts of the magnetic refrigerator can be easily lowered by improving its efficiency; for example, even if the efficiency of the magnetic refrigerator is further increased by 21% to have the same climate change impact as has the conventional refrigerator (see Fig. 7), it still has higher impact on the environment in the remaining categories except for human toxicity, ionizing radiation, freshwater eutrophication, marine eutrophication, and marine eco-toxicity.

4. Discussion and conclusions

This study indicates that the magnetic refrigerators have larger environmental impacts mainly due to the use of rare-earth metals in their magnet assembly. This shortcoming will be more pronounced if a rather clean energy mix is used during the use phase because of the increase of the relative share of the magnetic materials from the total environmental impacts. Nevertheless, the environmental loads associated with the rare-earth magnets can be abated by implementing regulations mandating the reuse of magnetic materials. Alternatively, if a magnetic refrigerator, through advanced design, can provide the same cooling power with reduced amount of magnetic materials, the added environmental burdens associated with the magnetic materials can be partly avoided. The best results are obtained when advanced design is accompanied by reuse of magnetic materials at end-of-life. It is noteworthy that research is ongoing to reduce or eliminate the share of rare-earth metals and to reduce the energy intensity of the processes in production of magnet materials, which lowers the environmental impacts of magnetic

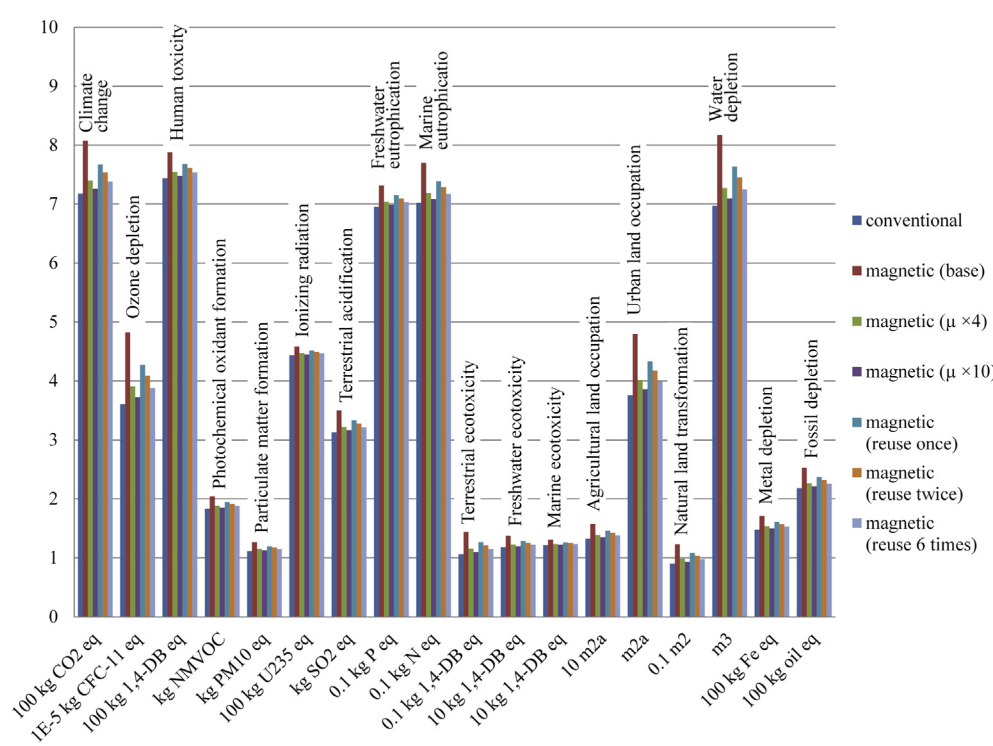

Fig. 5 – Characterization results for conventional refrigerator, magnetic refrigerator (base case), magnetic refrigerator with improved μ-values, and magnetic refrigerator with 90% reuse of magnetic materials.

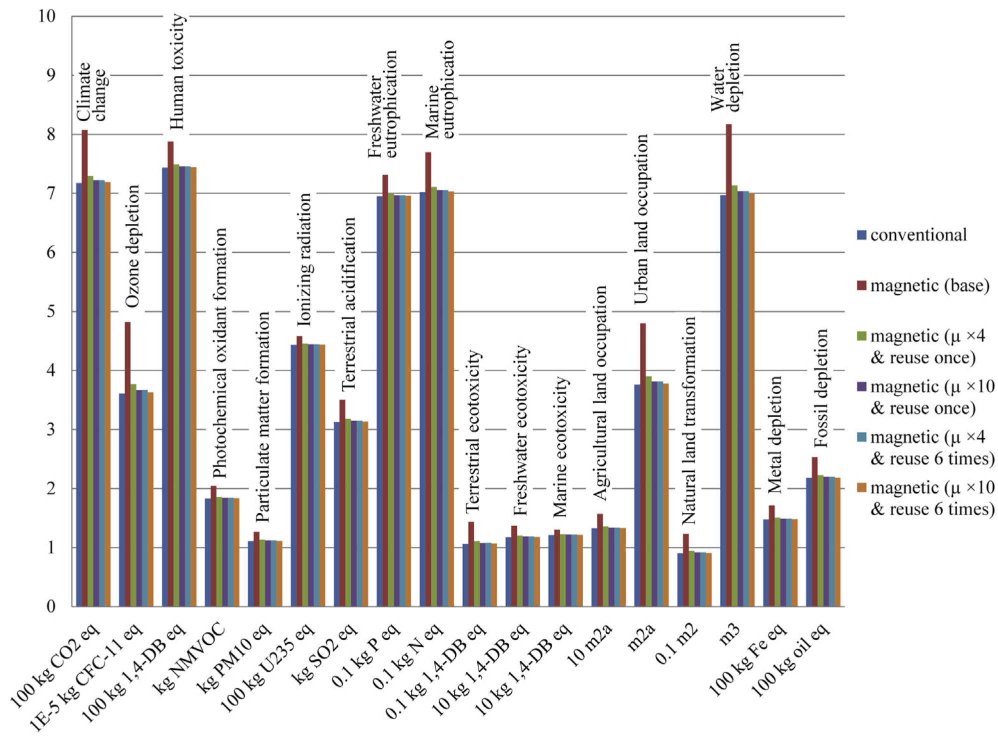

Fig. 6 – Characterization results for combination of reusing magnetic materials and improving μ-value.

refrigerators. The program Rare Earth Alternatives in Critical Technologies (REACT) launched by Advanced Research Projects Agency Energy (ARPA-E) and the working group European rare earths resource efficiency and recycling can be mentioned in this regard.

Improving the efficiency of the magnetic refrigerator may not compensate for all of the extra impacts of its production stage although it can make up for few impact categories. However, in larger refrigerators or refrigerator-freezers, where annual power consumption is higher, enhanced efficiency

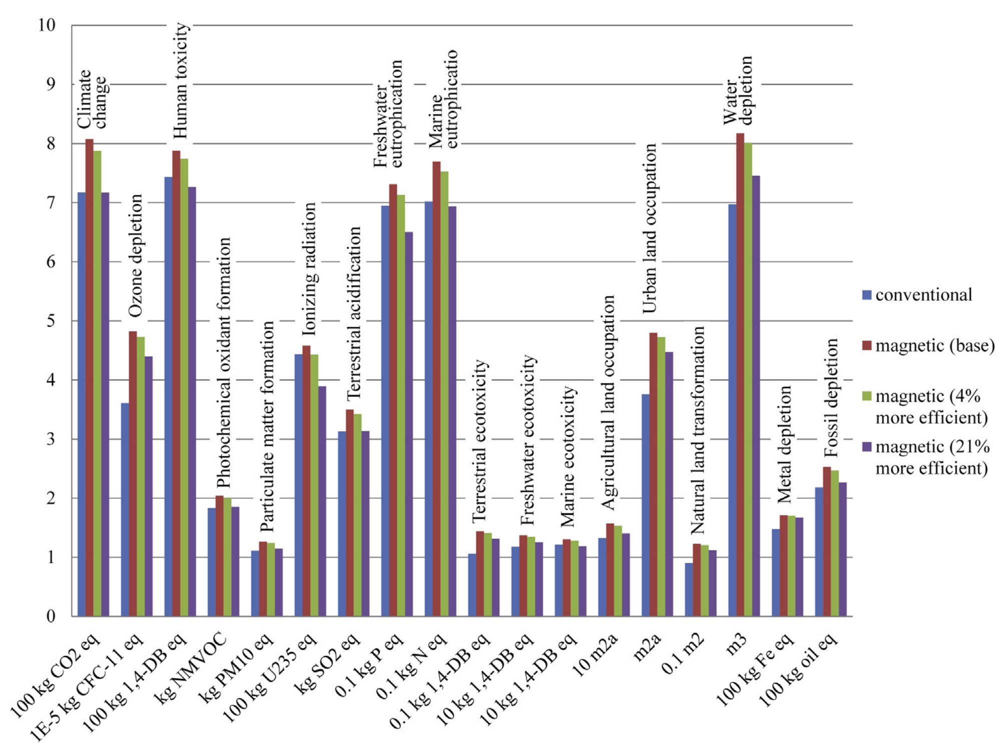

Fig. 7 – Effect of improved efficiency on the environmental impacts. (The functional units for the units with enhanced efficiency are different from that of the rest of the cases.)

can reduce the lifecycle environmental impacts more effectively.

The variations of the results by changing the efficiency of the refrigerator (translatable to use-phase energy consumption) can also be seen as a sensitivity analysis showing the importance of accurate estimation of the electricity consumption in a standalone LCA or in a comparative LCA where the use phases of the refrigerators are different. The sensitivity is not equal among all impact categories. In addition, higher sensitivity is expected with less-clean electricity mixes or higher μ-values, as the relative share of use phase electricity increases in both cases. However, the current study is less affected by such sensitivity since the use phases of the refrigerators are identical.

The choice of electricity mix to model the use phase is a critical stage in the LCA of the refrigerators for a standalone LCA since the impacts of the use phase has a major share in the total impacts. Even for the comparative LCA done in the current study, such choice alters the relative importance of the environmental burdens related to manufacture of magnetic materials. The choice of the electricity mix can be different for similar LCA studies depending on a number of factors such as the goal of the study and the geographical system boundary. Therefore, generalization of the results of this study should be done with care.

Acknowledgments

The authors would gratefully like to acknowledge that this study was financed by the Swedish Energy Agency, grant number 33847-1, and Electrolux through the research program EFFSYS+.

REFERENCES

Aprea, C., Greco, A., Maiorino, A., 2011. A numerical analysis of an active magnetic regenerative cascade system. Int. J. Energy Res. 35, 177–188.

Arnold, D.S., Tura, A., Rowe, A., 2011. Experimental analysis of a two-material active magnetic regenerator. Int. J. Refrigeration 34, 178–191.

Baumann, H., Tillman, A.M., 2004. The Hitchhiker's Guide to LCA: an Orientation in Life Cycle Assessment Methodology and Application. Studentlitteratur, Lund.

Bjørk, R., Bahl, C.R.H., Smith, A., Pryds, N., 2010. Review and comparison of magnet designs for magnetic refrigeration. Int. J. Refrigeration 33, 437–448.

Campbell, P., 1994. Permanent Magnet Materials and Their Applications. Cambridge Univ. Press, Cambridge.

Du, X., Graedel, T.E., 2011. Global rare earth in-use stocks in NdFeB permanent magnets. J. Ind. Ecol. 15, 836–843.

Engelbrecht, K., Bahl, C.R.H., Nielsen, K.K., 2011. Experimental results for a magnetic refrigerator using three different types of magnetocaloric material regenerators. Int. J. Refrigeration 34, 1132–1140.

Engelbrecht, K.L., Nellis, G.F., Klein, S.A., 2006. Predicting the performance of an active magnetic regenerator refrigerator used for space cooling and refrigeration. HVAC&R Res. 12, 1077–1095.

Faberi, S., 2007. Preparatory Studies for Eco-design Requirements of EuPs. LOT13: Domestic Refrigerator & Freezers.

Goedkoop, M., Heijungs, R., Huijbregts, M., De Schryver, A., Struijs, J., Van Zelm, R., 2013. Recipe 2008, a Life Cycle Impact Assessment Method Which Comprises Harmonised Category Indicators at the Midpoint and the Endpoint Level. The Hague.

Granryd, E., Ekroth, I., Lundqvist, P., Melinder, Å., Palm, B., Rohlin, P., 2011. Refrigerating Engineering. Royal Institute of Technology, KTH, Stockholm.

Gschneidner Jr., K.A., Pecharsky, V.K., 2008. Thirty years of near room temperature magnetic cooling: where we are today and future prospects. Int. J. Refrigeration 31, 945–961.

Kitanovski, A., Diebold, M., Vuarnoz, D., Gonin, C., Egolf, P.W., 2008. Application of Magnetic Refrigeration and Its Assessment: a Feasibility Study. Swiss Federal Office of Energy.

Muller, C., Bour, L., Vasile, C., 2007. Study of the efficiency of a magnetothermal system according to the permeability of the magnetocaloric material around its curie temperature. In: 2nd IIF-IIR Int. Conf. Magn. Refrig. Room Temp. IIF/IIR, Portoroz.

Pecharsky, V.K., Gschneidner Jr., K.A., 1999. Magnetocaloric effect and magnetic refrigeration. J. Magn. Magn. Mater. 200, 44–56.

Schüler, D., Buchert, M., Liu, R., Dittrich, S., Merz, C., 2011. Study on Rare Earths and Their Recycling: Final Report for The Greens/EFA Group in the European Parliament. Öke-Institut e.V, Darmstadt.

Thanh, D.T.C., Bruck, E., Trung, N.T., Klaasse, J.C.P., Buschow, K.H.J., Ou, Z.Q., Tegus, O., Caron, L., 2008. Structure, magnetism, and magnetocaloric properties of $MnFeP_{1-x}Si_x$ compounds. J. Appl. Phys. 103, 07B318–3.

Yu, B., Liu, M., Egolf, P.W., Kitanovski, A., 2010. A review of magnetic refrigerator and heat pump prototypes built before the year 2010. Int. J. Refrigeration 33, 1029–1060.