Project No.: 636881
Project acronym: REProMag

Project title:
Resource Efficient Production Route for Rare Earth Magnets

Programme: H2020-FoF-2014
Start date of project: 01.01.2015
Duration: 36 months

Deliverable 7.6

Final Environmental and Economic Report: Considerations and Future Guidance

Author: Will Jones
Due date of deliverable: M36 31/12/2017 **Actual submission date:** M36 27/12/2017

Deliverable Name	Final Environmental and Economic Report: Considerations and Future Guidance
Deliverable Number	D7.6
Work Package	WP7
Associated Task	7.4
Covered Period	M24-M36
Due Date	M36 (December 2017)
Completion Date	27/12/2017
Submission Date	29/12/2017
Deliverable Lead Partner	TEKS
Deliverable Author	Will Jones
Version	**1.3**

Dissemination Level		
PU	Public	**X**
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

Project funded by the European Union's
Horizon 2020 research and innovation programme

Change Control

Document History

Version	Date	Change History	Author(s)	Organisation
1.0	12th October 2017	Document drafted	Will Jones	TEKS
1.1	21st December 2017	LCA and LCC results added	Will Jones	TEKS
1.2	27th December 2017	Final conclusions added	Will Jones	TEKS
1.3	27th December 2017	Technical review	Will Thomas	TEKS

Distribution List

Date	Issue	Group

Table of Contents

Summary

WP7 considers the environmental and economic impact of the state-of-the-art production of rare earth (RE) magnets and then the newly developed REProMag Solvent Debinding and Sintering (SDS) method of RE magnet production.

The environmental and economic assessment will be carried out by a series of life cycle assessments (LCA) and life cycle costing (LCC). The LCA will be carried out on the current production route of RE magnets (from Inner Mongolia, China) and then compared to the SDS production route to show the environmental benefits of REProMag. As well as this an LCC will be conducted on the SDS method to quantify and then evaluate the economic costs associated with producing RE magnets via the SDS method. This has been done in the previous deliverables associated with this work package - D7.2 *Life Cycle Assessment Benchmarking and Report for Conventional Manufacturing*, D7.4 *Life Cycle Assessment Benchmarking and Report for the SDS Manufacturing Method* and D7.5 *Life Cycle Cost Report*.

This deliverable aims to bring together all the elements of the above mentioned deliverables in an overall environmental and economic report with considerations for the future.

1. Introduction

The REProMag project has been developed to help create and validate a new, more efficient method of producing RE magnets. The magnets are subject to several requirements - they must be economically efficient to manufacture with a complex structure and geometry. The magnets must also be 100% waste free along the whole manufacturing chain. These magnets can then be applied to a wide variety of applications including (but not limited to) electric motors, sensors, actuators, grippers and fixations in several different fields including (electro-) mobility, energy aerospace, industrial, mechanical engineering and medical technologies. These magnets will be produced using the new SDS method of production developed for the REProMag project.

SDS allows the sustainable production of magnets as it aims to use 100% recycled material which can subsequently be recycled at the end of its life. This not only reduces the over-reliance on Chinese controlled markets but also of benefit to the environment and the workers exposed to the poor conditions of the Chinese production routes. As well as this the energy efficiency along the manufacturing line is increased by 30% and waste material is significantly reduced compared to conventional machined magnets.

To measure the environmental and economic impacts of REProMag, life cycle assessments and life cycle costing have been carried out. These processes will be explained in the sections below with relation to the REProMag project.

2. Background and Methodology of LCA

The background and methodology has been outlined significantly in D7.2 - Life Cycle Assessment Benchmarking and Report for Conventional Manufacturing and D7.4 - Life Cycle Assessment Benchmarking and Report for the SDS Manufacturing Method, so only a brief background will be outlined here.

Industrial processes and systems have an input of raw material and energy. A by-product of production waste is produced in the forms of solid, liquid and gaseous waste. Other inputs are associated with the use phase and end-of-life stage of a product to quantify and assess the impact of products, processes and systems. A methodology is required to qualify and quantify environmental impacts , this methodology then allows, after analysis, reduction in emissions, pollutants and waste whilst protecting natural resources.

Awareness from consumers and environmental regulations have created a demand for more environmentally friendly productions. Traditional characteristics of cost, performance and quality are now more linked with the environmental impact of a product in terms of emissions released and resources consumed during the product's life cycle. As a result of this awareness, life cycle thinking was born and life cycle analysis was developed.

A life cycle assessment can be carried out for a singular industrial process, over a product's entire life cycle (cradle to grave), over a factory process (gate to gate) or any combination depending on the boundary conditions defined in the product outline.

- **Goal and Scope Definition:** In this phase the main objectives of the study are identified. A functional unit is defined - this is a reference quantity taken into account in the environmental balance. Geographical and time-related boundaries are accounted for, as is the energy mix and all assumptions and limitations. A flow chart is often constructed - this has been the case for REProMag.
- **Life cycle inventory (LCI):** In this stage the energy and raw material flow is built and assessed. This consists of inputs of raw materials, fuels and energy and outputs of solid, liquid and gaseous wastes. During this phase the data is collected on the consumptions and emissions for each step of the products life cycle. Primary data is collected from project partners and if required secondary data from literature, databases or previous studies is used.
- **Life cycle impact assessment (LCIA):** The data collected in previous phases is evaluated, processed and classified into the environmental impact categories as recognised by International Organisations (UNEP and SETAC). All the LCA results for REProMag were generated and assessed using GaBi 6 (ThinkStep).
- **Life cycle interpretation and improvement:** The final phase of the LCA study, the results are analysed and critical steps in the process are identified. Possible alternatives are suggested for materials, technologies, use of recycled materials and an increase in recycling etc in order to reduce the environmental impacts.

The LCA methodology is standardised in the ISO 14040 series and the LCA for REProMag has been carried out using The International Reference Life Cycle Data System (ILCD) handbook published by the Joint Research Centre (JRC) in 2010.

In REProMag the state-of-the-art production route was assessed, the assessment was carried out on the most common production route of rare earth (RE) magnets from the Bayan Obo mine in Inner Mongolia, China. An LCA was carried out on this production route and then a second on the SDS route developed for the REProMag project. These were then compared to see the environmental benefits of REProMag when compared with the state-of-the-art.

The process of mining and producing magnets is a dirty one; there has been negative coverage in the press. The workers in the mines are exposed to unpleasant conditions that can cause many health issues. Combined with a reliance on a Chinese market there is need and desire to create sustainable magnets from recycled material. By highlighting the dangerous nature of RE magnet production in the press and quantifying it with an LCA the argument for clean magnets has never been stronger.

All data collected is stored and protected in accordance with appropriate legislation and directives.

For REProMag partners are spread across Europe, meaning that components for the magnets (powder, for example) must travel long distances to reach the next stage of production with the next partner. This is unrealistic of an industrial process, so the SDS process was condensed down into a single facility in Germany with scrap being imported from Sweden. This was then compared to the production methods in China. The results of the LCA are unsurprising; it is an environmental benefit to produce the magnets in Germany using recycled material than mining virgin material in China.

The following processes chains were identified and evaluated for the purposes of the LCA:

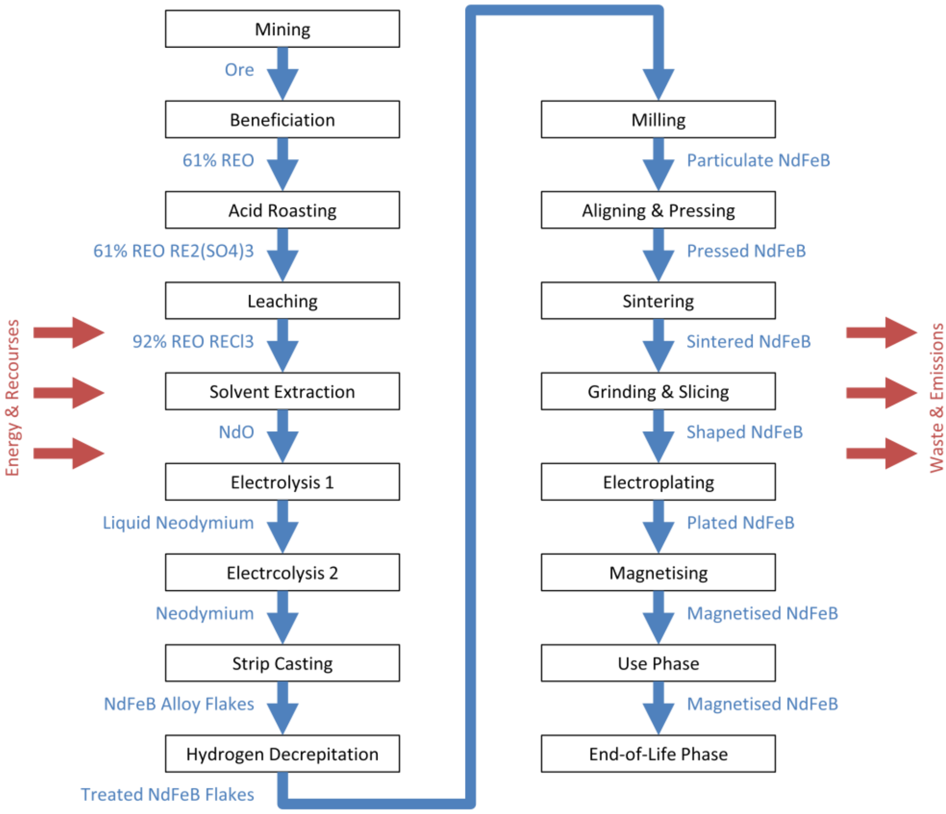

Figure 1 - State-of-the-art process chain.

For the SDS production route there are slight variations. The magnets are either metal injection moulded or 3D printed and are electroplated of subject to LPPS coating.

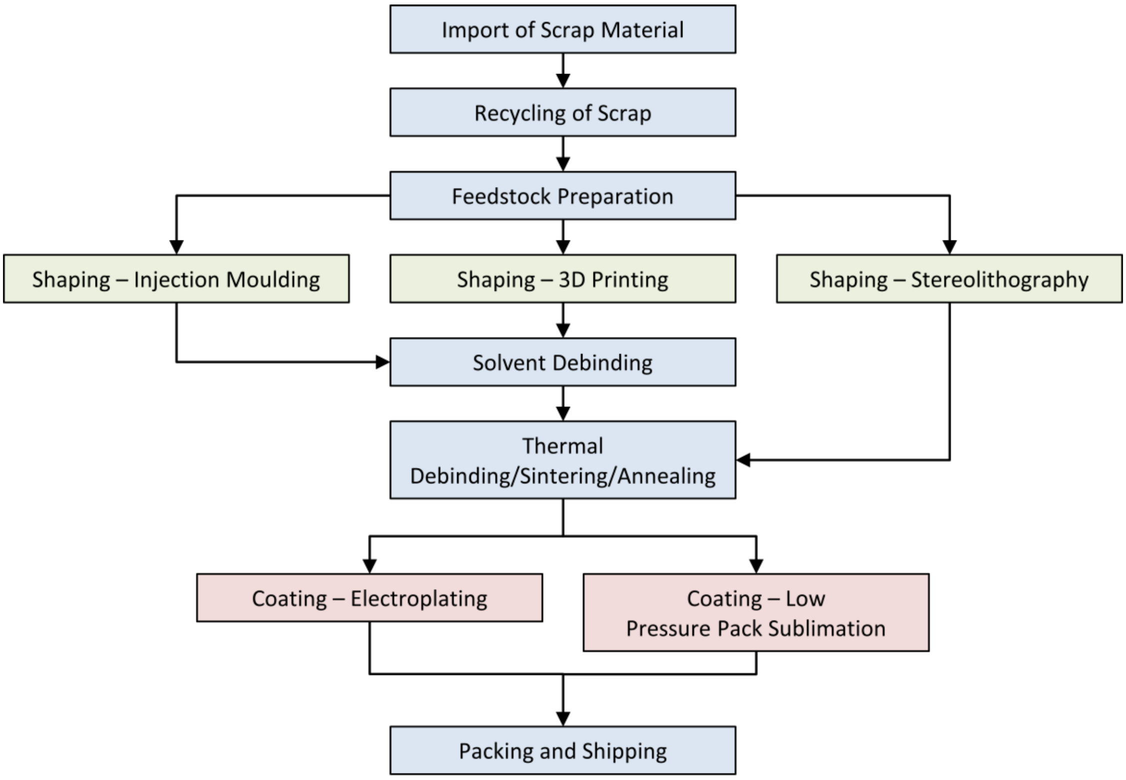

Figure 2 - SDS production routes.

3. Background and Methodology of LCC

The energy and materials used by a system depend on the design of the system in question, how it is installed into a facility and how the system is operated by the user. These factors are interdependent and moreover in the most cost effective facilities, they are carefully matched to each other. They remain so throughout their working lives ensuring the lowest energy cost, lowest maintenance cost, longest equipment life and other benefits. The initial purchase price of equipment is often seemingly high; however, it is a small part of the life cycle cost for high-usage machinery. Operating requirements may - in some cases - override energy cost considerations an optimum solution is still possible.

A greater understanding of all the components that make up the total cost of operation will provide an opportunity to reduce energy, operation and maintenance costs. Reducing energy consumption and waste also has important environmental benefits which will be discussed in other related deliverables.

This is the basis for the life cycle cost (LCC) assessment. It allows end users to indentify expensive aspects/areas of a production process and reduce them. As with the LCA a fictional facility has been created and scrap imported from an external site. As before this was to make the process more comparable to actual industrial processes.

Data was collected from partners and stored and protected in accordance with appropriate legislation and directives. LCC is a management tool that can help companies minimise waste and maximise energy efficiency for many types of systems or production routes including forming processes such as the ones used in REProMag.

The life cycle cost of any piece of equipment is the total lifetime cost to purchase, install, operate, maintain and dispose of that equipment. Determining the LCC involves the following methodology to identify and quantify all of the components of the LCC equation. Many organisations only consider the initial purchase and installation costs of a system. It is in the fundamental interest of the factory designer or manager to evaluate the LCC of different solutions before installing new equipment or carrying out a major overhaul. In this case we will be evaluating the production method of NdFeB magnets in a new facility importing scrap material, recycling and creating new magnets in one factory. As national and global markets become more competitive organisations must continually seek cost saving strategies that will improve the profitability of their operations. Machine equipment operations are receiving particular attention as a source of cost savings, especially minimising energy consumption and machine downtime.

In addition to the economic reasons for using LCC, many organisations are becoming increasingly aware of the environmental impact of their businesses and are considering energy efficiency as one way to reduce emissions and preserve natural recourses. LCC considers the initial cost/purchase price, installation and commissioning, energy costs, operation costs, maintenance and repair costs, downtime and loss of production costs, environmental costs, decommissioning/disposal costs and material costs. These are added together to give the total life cycle costs.

4. LCA Results Comparison and Discussion

The results from both LCA studies are detailed in this section below. There is one scenario for the state-of-the-art and four different scenarios for the SDS process. These different scenarios are based on the different production routes in the SDS process - differing shaping and coating methods. For specific details of the state-of-the-art LCA and the SDS LCA please see the associated deliverables.

The results of the analysis have been assessed in accordance with the ILDC recommendations based upon climate change (including and excluding biogenic carbon), ozone depletion, human toxicity (including and excluding cancer effects), particulate matter/respiratory inorganics, ionising radiation, photochemical ozone formation, acidification, eutrophication, ecotoxicity and recourse depletion. The impact categories are outlined below in table 1.

Impact Category	Unit	Definition
Global Warming Potential	kg CO_2 Equiv.	How much heat is trapped in the atmosphere by greenhouse gasses.
Ozone Depletion	kg R11 Equiv.	Reduction/depletion of the ozone which allows increased transmission of UV rays and has negative impacts on humans and plant life.
Human Toxicity, Cancer Effects	CTUh	Toxic to humans and are carcinogenic.
Human Toxicity, Non-Cancer Effects	CTUh	Toxic to humans but are not carcinogenic.
Particulate Matter/Respiratory Inorganics	kg PM2,5 Equiv.	Solids particles or liquid droplets that are dispersed in the air and considered air pollutants.
Ionising Radiation, Human Health	kBq U235 Equiv.	The potential damage to human health and ecosystems from emissions of radionuclides.
Photochemical Ozone Formation	kg NMVOC Equiv.	The formation of smog from photochemical oxidants.
Acidification	Mole of H+ Equiv.	Acid air emissions that have a negative effect on natural ecosystems.
Eutrophication, Terrestrial	Mole of N Equiv.	Ecosystem responses to aerial nitrogen compounds.
Eutrophication, Aquatic, Freshwater	kg P Equiv.	Nutrients simulating the growth and bloom of algae and plants. This in turn clogs water ways and may cause toxic blooms.
Eutrophication, Aquatic, Marine	kg P Equiv.	Nutrients simulating the growth and bloom of algae and plants. This in turn clogs water ways and may cause toxic blooms.
Ecotoxicity	CTUeco	Harmful effects on ecosystems.
Recourse Depletion, Water	m^3 Equiv.	The depletion/reduction of water.
Recourse Depletion, Mineral, Fossil and Renewable	kg Sb Equiv.	The depletion/reduction of raw materials.

Table 1 - Impact categories.

The results for the state-of-the-art LCA and the SDS LCA are outlined in table 2 below:

		S-o-t-A	SDS			
Impact Category	**Unit**		**MIM w/ Elec**	**MIM w/LPPS**	**3D Printing w/ Elec**	**3D Printing w/ LPPS**
Global Warming Potential	kg CO_2 Equiv.	18.30	11.60	8.16	11.90	10.90
Ozone Depletion	kg R11 Equiv.	2.62E-10	7.43E-11	1.50E-10	7.16E-11	1.63E-10
Human Toxicity, Cancer Effects	CTUh	1.91E-07	3.08E-08	1.28E-08	3.05E-08	1.46E-08
Human Toxicity, Non-Cancer Effects	CTUh	2.20E-06	6.77E-08	1.11E-07	2.79E-08	5.81E-08
Particulate Matter/Respiratory Inorganics	kg PM2,5 Equiv.	4.28E-02	4.23E-03	2.20E-03	4.22E-03	2.45E-03
Ionising Radiation, Human Health	kBq U235 Equiv.	0.24	1.17	0.96	1.02	1.26
Photochemical Ozone Formation	kg NMVOC Equiv.	5.07E-02	1.77E-02	1.06E-02	1.70E-02	1.37E-02
Acidification	Mole of H+ Equiv.	1.33E-01	5.19E-02	1.70E-02	5.09E-02	2.21E-02
Eutrophication, Terrestrial	Mole of N Equiv.	1.78E-01	6.88E-02	4.49E-02	6.40E-02	5.81E-02
Eutrophication, Aquatic, Freshwater	kg P Equiv.	1.50E-04	7.17E-05	5.64E-05	6.41E-05	6.50E-05
Eutrophication, Aquatic, Marine	kg P Equiv.	1.56E-02	6.84E-03	4.63E-03	6.31E-03	5.99E-03
Ecotoxicity	CTUeco	7.66E+00	8.11E-01	2.04E+00	8.36E-01	2.09E+00
Recourse Depletion, Water	m^3 Equiv.	7.94E-02	1.79E-02	1.22E-02	1.55E-02	1.64E-02
Recourse Depletion, Mineral, Fossil and Renewable	kg Sb Equiv.	1.66E-04	1.80E-04	5.74E-03	1.83E-04	5.86E-03

Table 2 - LCA results for the state-of-the-art and SDS production routes.

The results above are graphed below in figures 3 to 16; table 3 shows the key to the figures.

Blue	State-of-the-Art
Red	MIM w/Electroplating
Green	MIM w/LPPS
Purple	3D Printing w/Electroplating
Cyan	3D Printing w/LPPS

Table 3 - Graph key.

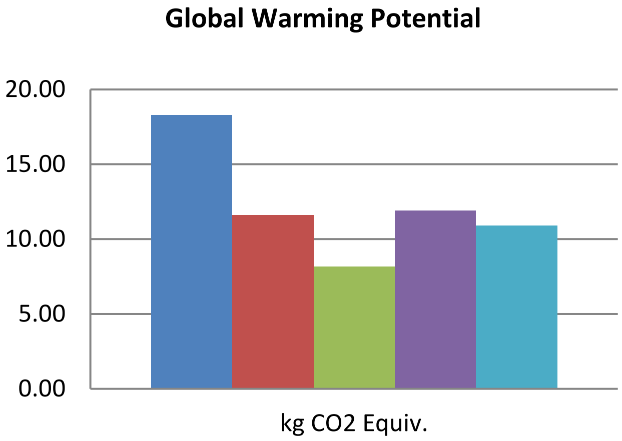

Figure 3

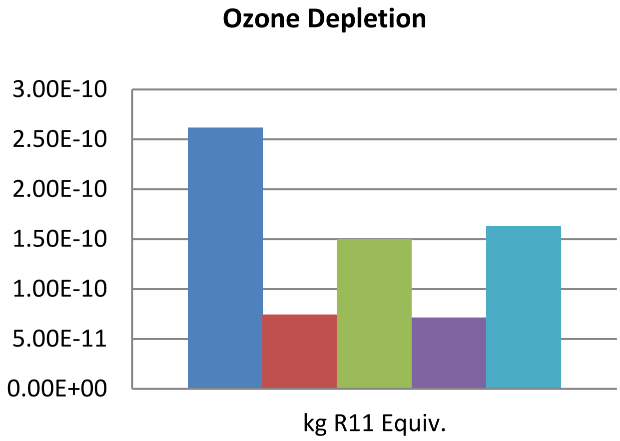

Figure4

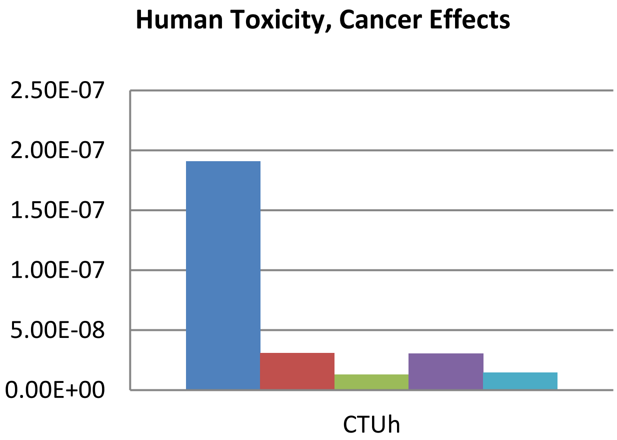

Figure 5

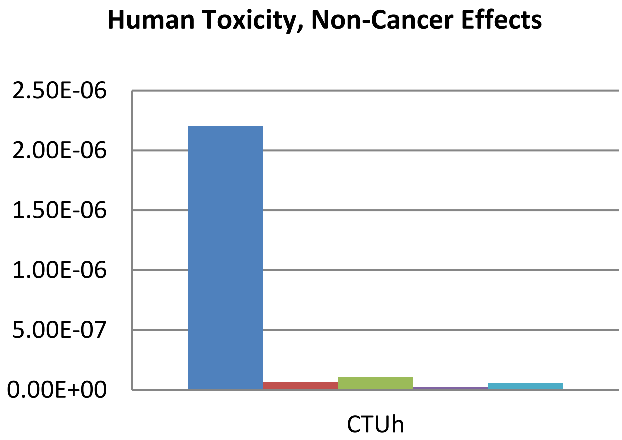

Figure 6

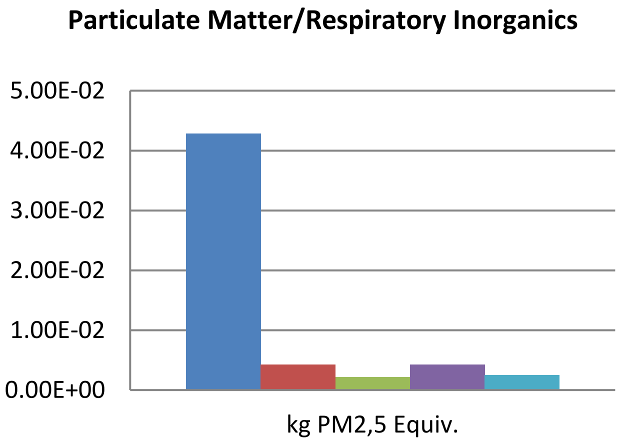

Figure 7

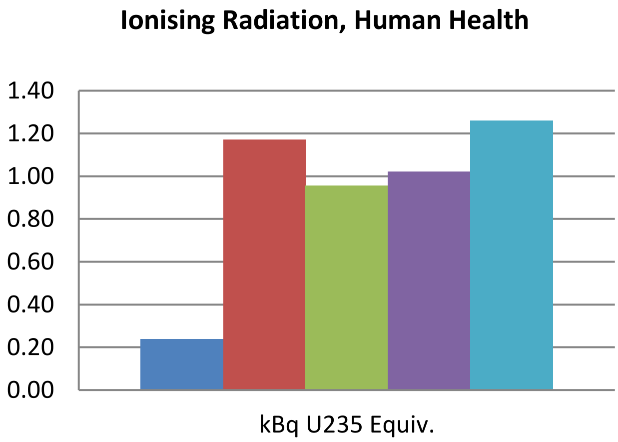

Figure 8

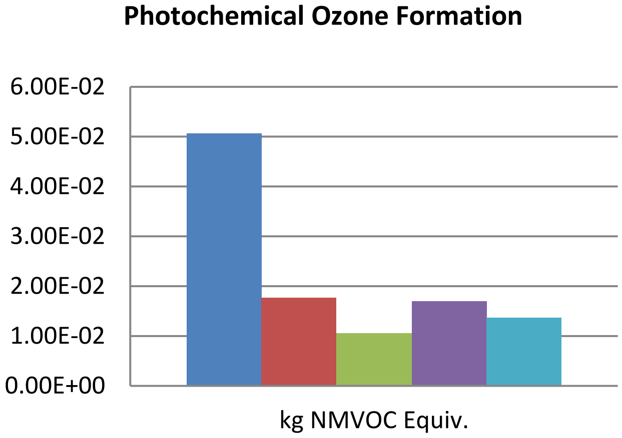

Figure 9

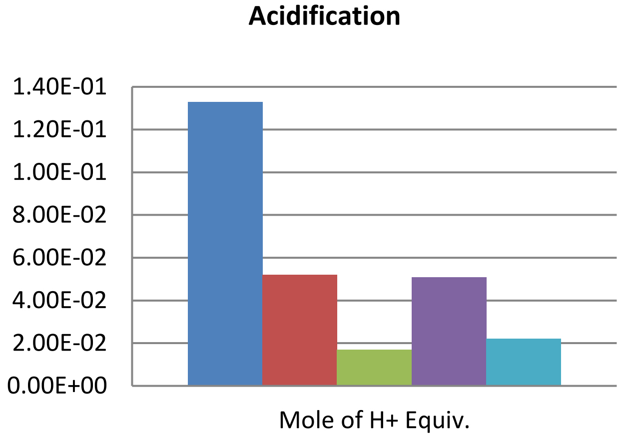

Figure 10

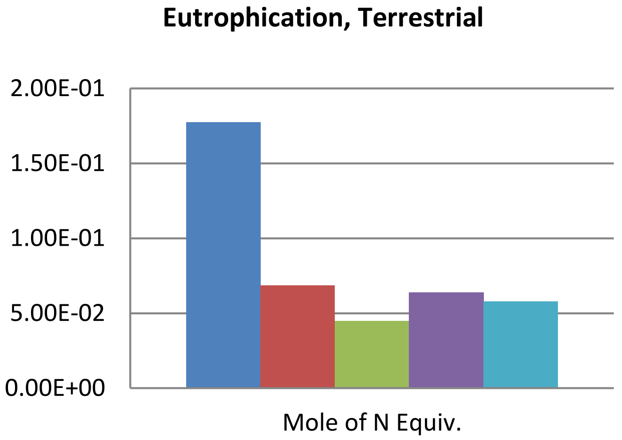

Figure 11

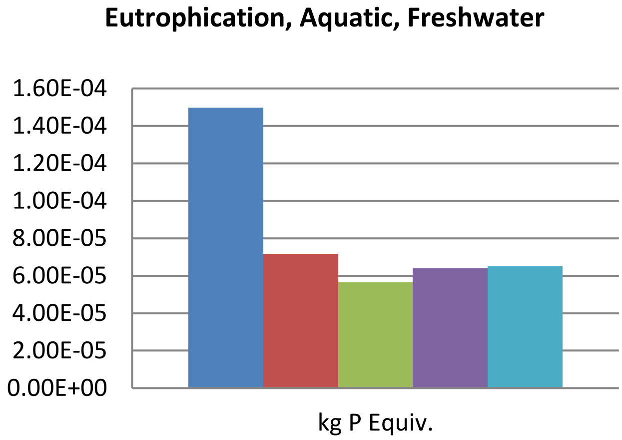

Figure 12

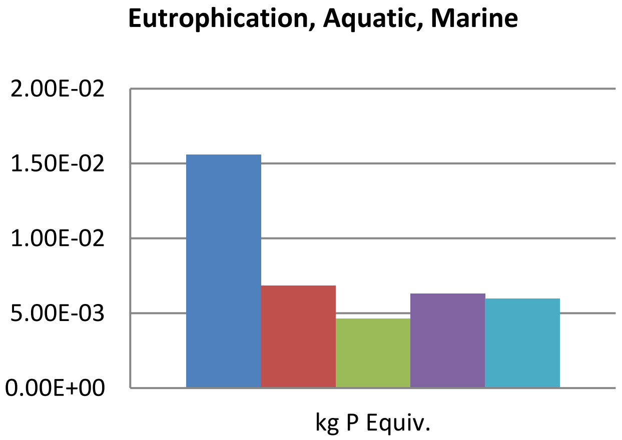

Figure 13

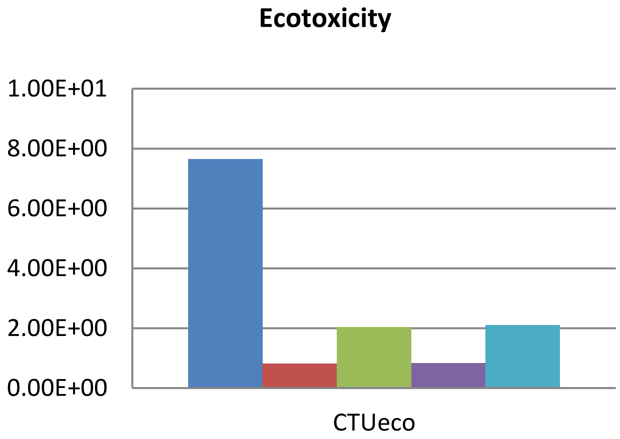

Figure 14

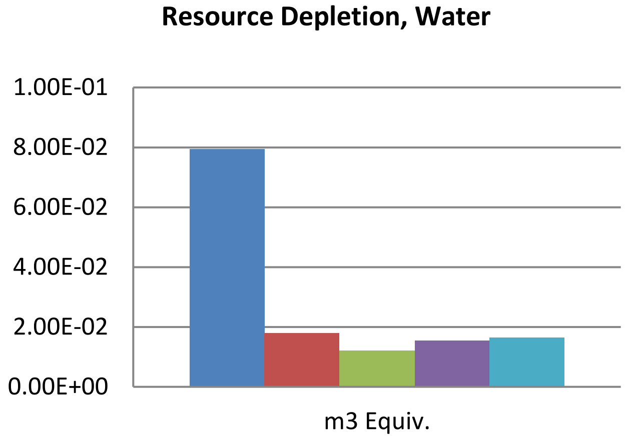

Figure 15

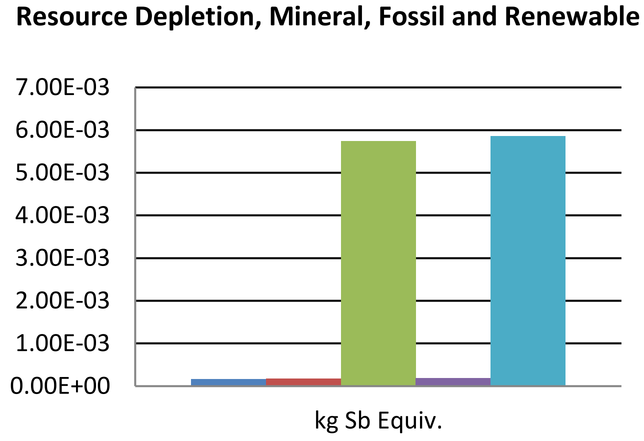

Figure 16

The graphs above show - on a consistent basis - that SDS magnets outperform Chinese produced magnets from almost all environmental impact categories. All SDS manufacturing routes are better than the state-of-the-art magnets, although there is some variation between the SDS manufacturing routes.

The outliers are figure 8 - Ionising Radiation, Human Health which is down to Germany's reliance on nuclear energy which makes up 13.1% of its energy production. In comparison to this, China's energy consumption is 2.1% nuclear. The ionising radiation however is far below any dangerous levels.

The other anomaly is the resource depletion - this takes into account resources being used during the production and not those produced. Therefore the mining process does not deplete resources but it creates them. As the LPPS process uses more resources than the others it is hence higher in its resource depletion.

5. LCA Conclusions

The results from the LCA show the SDS process in a positive light. In line with the European Union 7th Environment Action Programme, it reduces the amount of waste generated and maximises recycling and re-use.

There are areas for potential improvement. The SDS process is not currently an industrial one (despite the fact that the analysis is based on the contrary), and having partners around Europe and transporting materials between them has an adverse impact on the environment. Similar to this, creating or moving the recycling plant to the point of production would reduce travel related emissions transporting components to the recycling facility and then transporting them to the production facility.

6. LCC Results Comparison and Discussion

The results from the LCC are shown in table 4 below for the SDS process for MIM and 3D printing. The associated costs with the above production route have been provided by partners or found from literature.

The following table gives the related life cycle costs for the REProMag process broken down via manufacturing process. The table below is for production of 50,000 parts via metal injection moulding and 3D printing.

	REProMag LCC (MIM)	**REProMag LCC (3D Printing)**
Process	Cost Per Part (€)	
Transport	0.01	0.01
Recycling	0.01	0.01
Feedstock	0.20	0.20
Shaping	0.03	0.42
Debinding	0.17	0.17
Sintering	0.48	0.48
Heat Treatment	0.02	0.02
Personnel	0.22	0.22
Coating	0.02	0.02
Overhead inc. Profit	0.34	0.34
Total	1.50	1.89

Table 4 - LCC results for MIM and 3D printing.

This gives a total annual production cost (based on the production of 50,000 parts) of €75,000 for the MIM produced components and a cost of €94,500 for 3D printing.

The cost of a state-of-the-art magnet produced in China is €0.67 which is €0.83 cheaper than the SDS MIM magnet and €1.22 cheaper than the SDS 3D printed magnet. However, it is estimated that producing the Chinese magnet in Germany would cost €1.33 per part. This is €0.17 cheaper than the SDS magnet but uses virgin material and with the increased transportation (importing the material from China) would incur significant environmental impacts and not solve the issue of 'dirty magnets'.

7. LCC Conclusions

The cost of a state-of-the-art magnet produced in China is €0.67 per component which is €0.87 cheaper than the SDS MIM magnet and €1.22 cheaper than the SDS 3D printed magnet.

However, it is estimated that producing the Chinese magnet in Germany would cost €1.33 per part. This is €0.17 cheaper than the SDS magnet but uses virgin material and with the increased transportation (importing the material from China) would incur significant environmental impacts and not solve the issue of 'dirty magnets'.

Therefore the increased cost of SDS production in Europe is overshadowed by the increased environmental benefit of SDS production.

8. Overall Conclusions

As discussed several times throughout this report there is an environmental benefit to producing NdFeB magnets via the SDS production route rather than the current state-of-the-art. Whilst the SDS magnets do not outperform the state-of-the-art from an economic viewpoint this is unsurprising as the cost of production in China is low and standards for workers are not as stringent. The cost of producing an SDS magnet via MIM is €1.50 (based on the production of 50,000 parts) which is €0.83 more expensive than NdFeB magnets produced in China.

There are some variations with the environmental impacts between production methods used in the SDS process, these however are minor when compared to the state-of-the-art. Different production routes should be chosen depending on purpose. It should also be noted that for high volumes of production MIM is the preferred production method with 3D printing being good for prototyping and shapes with extremely complex geometries.

The use of recycled NdFeB material to produce new magnets is a viable source of magnets. Based upon the results of this and previous reports there is clear environmental benefits to SDS production and despite the higher cost these are overshadowed by the huge environmental saving.