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# Deliverable 7.4

## Life Cycle Assessment Benchmarking and Report for the SDS Manufacturing Method

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# Change Control

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## Summary

As previously discussed in other deliverables the overarching objective of REProMag is to develop and validate a manufacturing route for the Shaping, Debinding and Sintering (SDS) method of rare earth (RE) magnet processing. The aim of WP7 is to evaluate REProMag from an economic and environmental perspective and then provide conclusions and advice for the future.

The SDS method must consider economic and resource efficiency whilst also producing a net-shape magnet with a complex geometry whilst being waste free and using recycled material. Earlier in D7.2 - *Life Cycle Assessment Benchmarking and Report for Conventional Manufacturing* the current manufacturing route was assessed. This was based on the production of NdFeB magnets from the Bayen Obo mine in Inner Mongolia, China.

D7.2 served as a basis for the comparison of the state-of-the-art method of production and the SDS method - these two will then be compared and evaluated in D7.6 - *Final Environmental and Economic Report: Considerations and Future Guidance*.

In this deliverable a life cycle assessment (LCA) will be carried out on the SDS process created within the REProMag project. As with D7.2 the LCA will be cradle to grave over the whole life cycle and this particular deliverable will contain no economic evaluation - that is outlined in D7.5 - *Life Cycle Cost Report*.

# 1. Introduction

This deliverable (D7.4) relates to Task 7.2.2 - *Life Cycle Assessment Benchmarking and Report for the SDS Manufacturing Method* and will consider the environmental impact of the SDS method of production. In later deliverables this will be combined with previous work and then be compared with the current method of production to the see the environmental benefits of REProMag.

Environmental assessments are growing in popularity as there is more of a demand for 'cleaner' products. There are economic and environmental drivers behind the development of the SDS method. Whilst from an economic perspective over reliance on Chinese imports is a focal point this report will consider the environmental effects only.

There have been several reports in various media outlets about the environmentally dangerous procedures surrounding NdFeB magnet production. In 2011 the Mail Online ran an article entitled "In China, the true cost of Britain's clean, green wind power experiment: Pollution on a disastrous scale" (Parry & Douglas, 2011)in which it looks at the poor conditions that workers are exposed to and the effect of the mining on the local environment.

Hence one of the main objectives of REProMag is to be 100% waste free and use recycled material. By using recycled material the reliance on Chinese markets is reduced and workers are not subject to toxic substances and carcinogens. Finally there is an environmental benefit to using recycled material, reducing land destruction and damage, reducing emissions and preventing the toxification of land.

As with the previous study the production of 1kg of NdBeB magnets will be considered. The scrap NdFeB will be imported and then the production of the magnets will be considered to be in one facility. Currently with the REProMag process there is a mix of industrial and lab scale processes. Also the physical distance between the partners means that in some cases the power, magnets or other resources have to travel great distances at high monetary and environmental cost. This is not a true representation of the final process and as D7.2 concerned itself with a fully industrial process the REProMag one must be treated the same to be compared. Therefore in this evaluation several assumptions have been mad - these are all outline in the relevant sections of this report.

Whilst the production will be a representation of what takes place within the SDS process certain parts (such as laboratory scale processes) will have to be up-scaled. This will be done with the advice and guidance of partners within the consortium.

Partners have also provided data on the production of NdFeB magnets using the SDS process and this will be used throughout this evaluation.

## 2. Premise of an LCA

An outline of the premise of an LCA has been provided in D7.2. However, for the purpose of consistency it will be provided again within this report. The basic idea of an LCA does not change from study to study and is compliant with the standards and regulations listed below.

Industrial processes or activates involve an input of raw material and energy. As a result of production waste is produced in the form of solid waste and/or emissions to the environment. Further inputs and outputs are associated across different stages of a products life cycle. Therefore as a means of measuring and quantifying these emissions and by products life cycle assessments or LCAs are carried out with the overriding goal of reducing emissions, pollutants and waste and helping preserve natural resources.

Consumer awareness and environmental regulations have created a demand for more environmentally friendly products and processes. It is now in the public eye and a concern for the consumer. The traditional characteristics of cost, performance and quality are more linked with the environmental impact of a product in terms of emissions released and resources consumed during the products life cycle. This awareness has created 'Life Cycle Thinking' and life cycle analysis was developed. The LCA methodology is outlined in the four sections below:

**Goal and Scope Definition:** In this section the main objectives of the study are identified and highlighted. The Functional Unit it defined - the functional unit serves as a reference for all quantities taken into account in the environmental balance. Geographical and time-related boundaries are accounted for as is the energy mix and all the assumptions or limitations of the study. As before a flow chart will be created to map the production process.

**Life Cycle Inventory (LCI):** In this section the energy and raw material flow is assesses. This consists of inputs of raw materials, fuels and energy and outputs of solid, liquid and gaseous waste. During this phase the data is collected from partners and/or literature this consists of data regarding consumptions and emissions for each step of the life cycle. Primary data is collected from manufactures and secondary data from literature if required.

**Life Cycle Impact Assessment (LCIA):** The data collected in the life cycle inventory is evaluated, processed and classified into the Environmental Impact Categories as recognised by international organisations (UNEP and SETAC). The LCA results presented in this deliverable - as with D7.2 - will be generated using GaBi 6 by ThinkStep.

**Life Cycle Interpretation and Improvement:** This is the final phase of the LCA study. Once the objective has been defined, the analysis complete and the results obtained the final stage consists of identification of critical steps in the life cycle. From this identification improvements can be suggested in the manufacturing process or life cycle to reduce emissions and waste. Alternative technologies, materials or increased recycling etc can be employed to reduce the environmental impact of the product/system. In the case of REProMag the life cycle interpretation for both the state-of-the-art and the SDS process will go onto form D7.6 - *Final Environmental and Economic Report: Considerations and Future Guidance*.

The LCA methodology has been officially standardised with the creation of the ISO 14040 series. In these documents the guidelines for carrying our a correct and complete LCA study are provided. Since then on the 12$^{th}$ March 2010 the Joint Research Centre (JRRC) published the International

Reference Life Cycle Data System (ILCD) Handbook comprising of a series of seven books where the phases of the LCA studied are described and outlined in detail and all reference and updates of the methodology are provided. In REProMag the state-of-the-art production route has been analysed in D7.2. Based on a study conducted by Ben Sprecher of Yale School of Forestry & Environmental Studies the analysis concerned itself with the production or RE magnets from the Bayan Obo mine in Inner Mongolia, China. This is the current most likely source of the majority of the worlds RE magnets hence the importance of the study. (Sprecher, et al., 2014)

D7.2 provides an overview of the environmental impacts of the state-of-the-art production route and not a comprehensive evaluation or suggestion of improvements for that particular method of production. Instead D7.2 will serve as a basis of comparison. When the SDS method is evaluated in this deliverable the two methods will be compared in D7.6 with suggestions for improvements for the SDS method.

The first step of the application of the LCA methodology involves the identification and collection of data for each input process within the system boundaries. As well as the functional unit (see Goal and Scope Definition) is defined. A process flow diagram is developed to provide an understanding of all the inputs, outputs and flows. Figure 1 illustrates this for the SDS manufacture of NdFeB magnets.

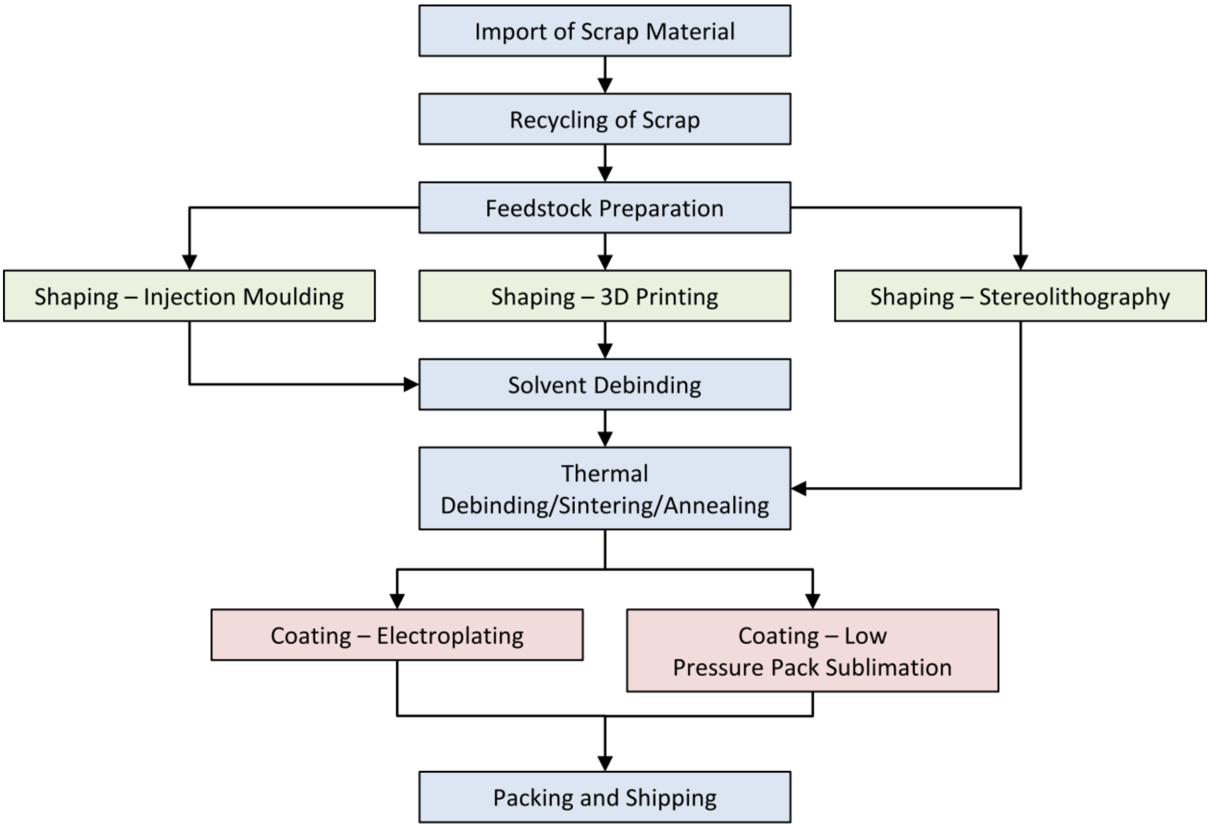


*Figure 1 - Process plan for the SDS manufacturing route.*

Each step in the process will be broken down into its sub processes further into this report during the LCI stage.

The process flow diagram in Figure 1 helps in the identification of relevant data that is required to conduct the life cycle assessment in the life cycle inventory stage. The collection of this data provides all the relevant information needed for modelling the environmental impacts of the SDS manufacturing route. Once the life cycle inventory is compete and the resource and emissions are quantified the LCA can be carried out.

All economic analysis will be carried out via a life cycle costing assessment in D7.3.

# 3. Goal and Scope

As with D7.2 this deliverable aims ot present a comprehensive life cycle assessment of the SDS process developed within REProMag. An LCA on the state-of-the-art production has been carried out in D7.2 this will then be compared for environmental impacts against the SDS method in D7.6. This is shown visually in Figure 2.

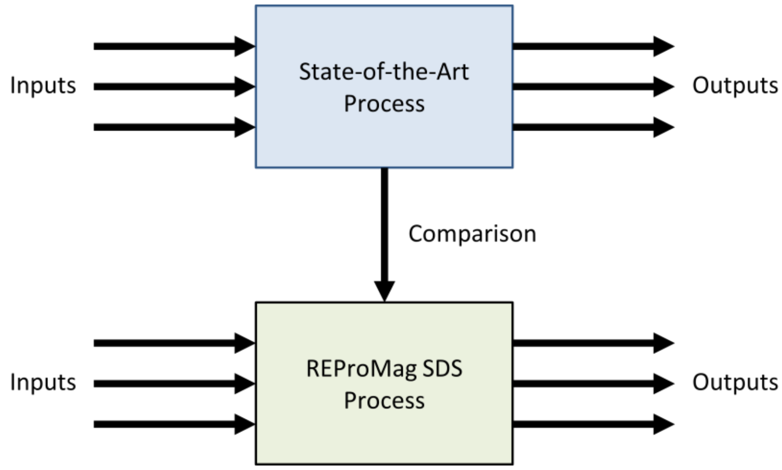


*Figure 2 - Simplified workflow for comparison of processes within REProMag.*

The source of the magnetic material is Halmstad, Sweden and will travel down to a production facility in Ispringen, Germany. Germany has been chosen as the location of production due to the end users within the consortium being Germany companies.

Due to the current status of the SDS production route certain assumptions will have to be made. Currently as partners within the consortium - those aiding the production of NdFeB magnets - are based all around Europe the material has to travel great distances before a final product is made. As well as this there are certain lab processes within the production route which are not representative of the final, idealised production method. In order to have a worthwhile comparison a fully fledged manufacturing process must be compared to the same therefore a fictional production facility will be created within Germany encompassing the entirety of the SDS process. This will elevate any unnecessary costs and emissions associated with transporting the material across large distances over Europe - something that is not representative of a true manufacturing process.

Certain lab processes within the project will be 'scaled-up' to again be representative of a real life manufacturing facility. This will then provide a more accurate comparison to the state-of-the -art and hence more worthwhile values for the environmental impacts and cost.

Again for comparison purposes the functional unit for the study will be the production and processing of 1kg of NdFeB magnets.

This deliverable will be used in a future comparison and will be compared against the state-of-the-art production of NdFeB magnets against the SDS method developed on the REProMag project. The aims of the comparison are to show the environmental benefits of REProMag over current sources of magnetic material. The study will be carried out using GaBi 6 by ThinkStep.

The target audience is the REProMag consortium which consists of industrial partners that manufacture and utilise magnetic material. The results from this LCA study will be compared against previous studies for comparison.

# 4. Life Cycle Inventory (LCI)

A common source of RE magnets is China - in particular the Bayan Obo mine in Inner Mongolia, China. This production route was analysed in D7.2 and encompasses the entire production from RE extraction through to the final part. This deliverable concerns itself with the SDS production route developed by partners on the REProMag project. Whilst the original source of the magnetic material is likely to be China (or a mine/production facility of equal environmental burden) the material used for REProMag is 100% recycled and is sourced from a scrap facility in Sweden. The recycling facility in the REMNANCE EU project (NMP2-SE-2012-310240) will be used - Stena Technoworld AB (Halmstad, Sweden) and will be transported to the production facility which will be assumed to be in house at OBE - REProMag project lead - (Ispringen, Germany).

**Importing of Scrap Material:** Scrap magnetic material - such as hard disk drives (HDDs) - are crushed and the magnets removed. From larger items (motors for example) the motors are removed by hand. Hand removing magnetic material is preferable as other types of recycling - such as shredding - yields lower amounts of recycled material. The magnetic material is then transported from the scrap facility to the production facility in Germany. The material will be transported by lorry on road. The distance between the two facilities is 1,147km.

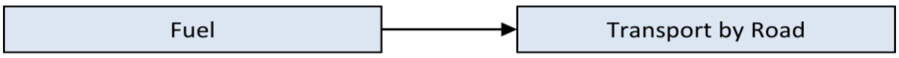


*Figure 3 - Importing of scrap material.*

**Recycling of Scrap:** Once the scrap arrives at the production facility it undergoes hydrogen decrepitation. NdFeB sintered magnetic material is exposed to a hydrogen atmosphere and the hydrogen slowly absorbs into the material making it brittle. This is then sieved and jet milled creating a fine powder.

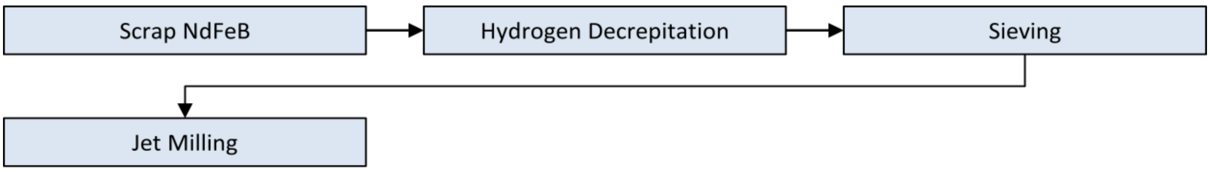


*Figure 4 - Recycling of scrap material.*

**Feedstock Preparation:** Particles are covered with additives before being blended with a binder. Finally the coated powder is subject to homogenisation and then extrusion or granulation depending on the shaping process. The feedstock preparation process is outlined for the three shaping processes in the figures below.

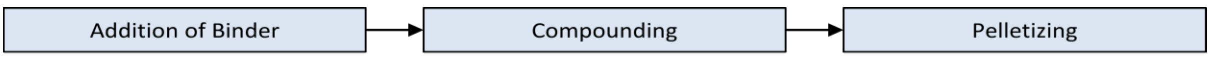


*Figure 5 - Feedstock preparation for metal injection moulding.*

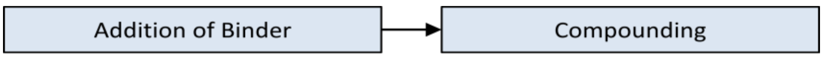


*Figure 6 - Feedstock preparation for 3D printing.*

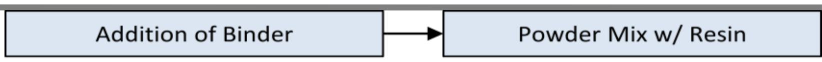


*Figure 7 - Feedstock preparation for stereolithography.*

**Shaping - Injection Moulding:** The magnetic material is forced into the cavity of the mould via an injection moulding machine. This is then exposed to a magnetic field to align the magnet before being extracted from the machine. After this stage the component is known as a 'green part'.


*Figure 8 - Metal injection moulding process.*

**Shaping - 3D Printing:** The magnetic filament is loaded into the 3D printing machine and heated within the printer head. It is extruded and subject to magnetic alignment exiting the printer nozzle. The component is built up layer by layer before it is allowed to cool and removed from the printer.


*Figure 9 - 3D printing process.*

**Shaping - Stereolithography:** Components are created layer by layer using photopolymerisation a process where light is exposed to a bath of liquid resin causing chains of molecules to link forming polymers making a three dimensional part. Each layer is magnetically aligned as each layer is created. Finally the part is allowed to cool before being removed.


*Figure 10 - Stereolithography printing process.*

**Solvent Debinding:** The debinding process removes the binder added in the feedstock preparation stage. Solvent debinding involves the use of water (and/or other chemicals such as acetone) as the binder is water soluble.

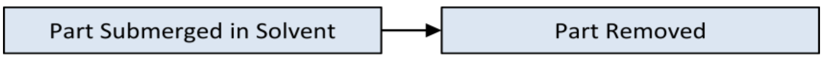


*Figure 11 - Solvent debinding of component.*

**Thermal Debinding and Sintering:** Thermal debinding is the removal of the binder using heat. The binder is simply evaporated without destroying the part. This final debinding process reduces the binder content significantly creating the 'brown part'. The part is then sintered reducing the overall size of the shape and increasing the density. This final process creates the final part.

*Figure 12 - Thermal debinding and sintering of component.*

**Coating - Electroplating:** The magnets are submerged in a solution containing dissolved nickel and then a current is passed both through the solution and through the magnets. The magnets have a negative charge and the solution a positive one. The positive nickel then coats the negatively charged NdFeB magnets.


*Figure 13 - Electroplating of NdFeB magnet.*

**Coating - Low Pressure Pack Sublimation (LPPS):** The magnets are packed into a bed of powered zinc and sand within a furnace tube. The furnace tube is then evacuated and then heated to around 400°C where the zinc sublimes and reacts with the surface of the magnet coating the magnet.


*Figure 14 - LPPS of NdFeB magnet.*

# 5. Life Cycle Impact Assessment

The results of the analysis have been assessed in accordance to 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. |
| fPhotochemical 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.*

There are six different combinations of production outlined in the tables below.

| **Impact Category** | **Unit** | **MIM w/ Electroplating** | **MIM w/LPPS** | **3D Printing w/ Electroplating** | **3D Printing w/ LPPS** |
|---|---|---|---|---|---|
| Global Warming Potential | kg $CO_2$ Equiv. | 1.160E+01 | 8.160E+00 | 1.190E+01 | 1.090E+01 |
| Ozone Depletion | kg R11 Equiv. | 7.430E-11 | 1.500E-10 | 7.160E-11 | 1.630E-10 |
| Human Toxicity, Cancer Effects | CTUh | 3.080E-08 | 1.280E-08 | 3.050E-08 | 1.460E-08 |
| Human Toxicity, Non-Cancer Effects | CTUh | 6.770E-08 | 1.110E-07 | 2.790E-08 | 5.810E-08 |
| Particulate Matter/Respiratory Inorganics | kg PM2,5 Equiv. | 4.230E-03 | 2.200E-03 | 4.220E-03 | 2.450E-03 |
| Ionising Radiation, Human Health | kBq U235 Equiv. | 1.170E+00 | 9.570E-01 | 1.020E+00 | 1.260E+00 |
| Photochemical Ozone Formation | kg NMVOC Equiv. | 1.770E-02 | 1.060E-02 | 1.700E-02 | 1.370E-02 |
| Acidification | Mole of H+ Equiv. | 5.190E-02 | 1.700E-02 | 5.090E-02 | 2.210E-02 |
| Eutrophication, Terrestrial | Mole of N Equiv. | 6.880E-02 | 4.490E-02 | 6.400E-02 | 5.810E-02 |
| Eutrophication, Aquatic, Freshwater | kg P Equiv. | 7.170E-05 | 5.640E-05 | 6.410E-05 | 6.500E-05 |
| Eutrophication, Aquatic, Marine | kg P Equiv. | 6.840E-03 | 4.630E-03 | 6.310E-03 | 5.990E-03 |

| | | | | | |
|---|---|---|---|---|---|
| Ecotoxicity | CTUeco | 8.110E-01 | 2.040E+00 | 8.360E-01 | 2.090E+00 |
| Recourse Depletion, Water | $m^3$ Equiv. | 1.790E-02 | 1.220E-02 | 1.550E+01 | 1.640E+01 |
| Recourse Depletion, Mineral, Fossil and Renewable | kg Sb Equiv. | 1.800E-04 | 5.740E-03 | 1.830E-04 | 5.860E-03 |

*Table 2 - Results from the LCA.*

# 6. Conclusions

In this analysis all the production routes have been analysed. An in-depth detailed conclusion and comparison of the results will be provided in D7.6 - *Final Environmental and Economic Report: Considerations and Future Guidance*. As with D7.5 the production is all housed within one facility in Germany this is to make the process a true representation of an actual industrial process and hence suitable for further comparison.