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Reduced use of rare earth elements for permanent magnet generators: preliminary results from NEOHIRE project

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Abstract

The use of so called Rare Earth Elements (REEs) for the production of permanent magnets (PMs) is increasing worldwide due to the needs of numerous industrial sectors. REEs are described in literature as critical materials due to the uncertainties related to cost instability and due to the potential environmental and social impact associated to their production cycle. The NEOHIRE project aims at reducing the amount of critical materials installed on wind turbine generators, developing bonded magnets characterized by reduced use of REEs. The project includes the study of alternative alloys and of their specific production processes, the engineering of machines optimized for the characteristics of the newly developed magnets, the proposal of recycling processes tailored for different types of PM; life cycle analyses aimed to estimate environmental, economic and social impact are also performed to verify the sustainability of the proposed technology. This paper describes the results of the first phase of such life cycle assessment, which started with inventory definition. The steps for PM production have been characterized, identifying materials, energy use and substances used as input; sintered PMs are used as reference for a comparison with bonded PMs. The construction of the inventory has been done considering small scale processes performed during research activity, which are characterized by a different specific energy consumption in relation to industrial-scale ones. Therefore, a thermal model for the assessment of the performances of scaled-up processes is proposed, being suitable for the estimation of energy consumption during heat-treatments. A provisional scenario for new bonded PMs production is then adopted for environmental impact assessment. Results, which have to be considered as preliminary, show the main relevance of various phases in determining the impact and a brief comparison with sintered PMs-based machines.

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1. Introduction

The use of Rare Earth Elements (REEs) for the production of permanent magnets (PMs) is increasingly worldwide due to the needs of multiple industrial sectors (Fernandez, 2017). Focusing on electrical machines, PM based on REEs can guarantee performances such as high coercitivity, being therefore suitable for the production of devices characterized by high efficiency, good controllability, relevant torque and power density (Widmer et al., 2015; Zhou et al., 2015). On the other side, REEs are described in literature as critical materials (Nassar et al., 2015) due to the uncertainties related to cost instability and due to the potential environmental and social impact associated to their production cycle; literature data highlight the need for REEs use reduction starting from machine optimization (Jahns, 2017). The NEOHIRE project (NEOHIRE, 2017) aims at reducing the amount of critical materials installed on Wind Turbine (WT) generators, developing bonded magnets characterized by reduced use of REEs. The project includes the study of alternative alloys and of their specific production processes, the engineering of machines optimized for the characteristics of the newly developed magnets, the proposal of recycling processes tailored for different types of PM, suitable methods being solvent treatment (Riaño et al., 2017) and others (Binnemans et al., 2013). Final aim is to reduce the kg of REEs use per each MW of nominal size of generator. Life cycle analyses aimed to estimate environmental, economic and social impact are also performed to verify the sustainability of the proposed technology.

This paper describes the results of the first phase of such life cycle assessment, which started with inventory definition. The steps for PM production have been characterized, identifying materials, energy use and substances used as input; sintered PMs are used as reference for a comparison with bonded PMs. The construction of the inventory has been done considering small scale processes performed during research activity, which are characterized by a different specific energy consumption in relation to industrial-scale ones. Therefore, a thermal model for the assessment of the performances of scaled-up processes is proposed, being suitable for the estimation of energy consumption during heat-treatments. A provisional scenario for new bonded PMs production is then adopted for environmental impact assessment. Results, which have to be considered preliminary due to the known limitations of the study, show the main relevance of various phases in determining the impact and a brief comparison with sintered PMs-based machines.

The document is organized as follows. Section 2 describes the approach adopted for Life Cycle assessment and the description of production process for bonded PMs. Section 3 provides the results of the preliminary LCA performed. Final observations and description of next research steps are presented in the conclusion section.

2. Performing Life Cycle Assessment for REEs Permanent magnets

The assessment of life cycle impact related to the extraction, production, use and recycling of REEs is under continuous updating and research in literature (Navarro and Zhao, 2014); in this section, the approach adopted for environmental impact is presented.

Life Cycle Assessment (LCA) is a methodology aimed to evaluate the environmental loads of processes and products (in terms of materials and energy) during their whole Life Cycle (LC) stages: processing of raw materials, manufacturing processes, use, maintenance, recycling and final disposal (End of Life, EoL). According to the framework defined by earlier and recent ISO standards (ISO, 2006a, 2006b), LCA (see Fig. 1) usually includes four stages:

1. Goals and Scope definition (G&S), in which the Functional Unit (FU) and system boundaries are defined.
2. Life Cycle Inventory (LCI). The data collection is the core of this analysis because it should consider all elements included in system boundaries (e.g. LC stages; Process Units, PUs) and flows in terms of both materials and energy inputs/outputs.
3. Life Cycle Impact Assessment (LCIA) which consists in classifying and characterizing data collected in the LCI; the final result of this stage is the quantitative evaluation and assessment of the environmental and economic outcomes.

4. Life Cycle Interpretation. In this phase a readily understandable, complete and consistent presentation of LCA results is provided, taking into account a sensitivity analysis.

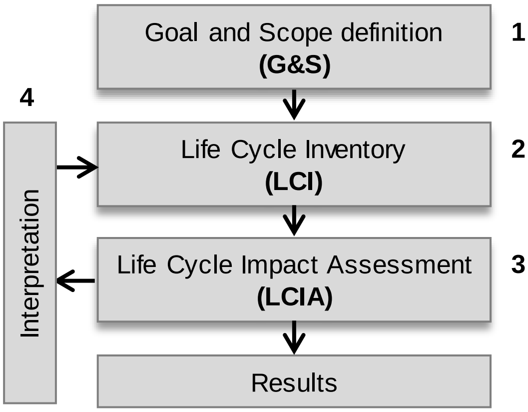

Fig. 1. The four stages of LCA.

In relation to the NEOHIRE activites, the goal is to evaluate the sustainability performances (in terms of environmental, economic and social issues) along the whole LC phases of two alternatives NdFeB PM for WT generators.

The scope is to verify and demonstrate the benefits of adopting new concept of bonded NdFeB magnet in substitution of the known sintered magnets for WT generators, assumed as reference.

The Functional Unit (FU) is therefore related to the use of NdFeB magnet on the specific application of large size WT generators (1-10MW range), for which a life of several years is expected (in the range of 20-30 years). A suitable option for FU is therefore the amount of NdFeB material used per MW installed or per MWh produced (kg/MW; kg/MWh). Considering that different performances are expected depending on the manufacturing technologies of the magnets (sintered PM; bonded PM; NEOHIRE bonded PM), such FU will be appropriate also for comparative assessments. However, in this phase, all the data will be expressed having on mind the impact for the production of 1kg of PM; the conversion on the final FU will be performed in final phases, when performance data related to the installation on the WT will be available after re-design of the machine according to bonded PM characteristics. System boundaries consists of all stages of the components life (from-cradle-to-crave) and in particular: materials production; manufacturing, use and End-of-Life (EoL).

GaBi software (Thinkstep, 2019) will be used to model the processes and to implement the LCA analysis.

The objective of this document is to describe the process itself and the methodology adopted for its assessment; since process data are still affected by uncertainties and limitations due to the experimental environment in which they have been performed, data about process fluids and additives (e.g. argon and nitrogen as inert atmosphere for processing; water) are not included as details, and will be published during further NEOHIRE developments; declared data include PM material definition and main energy consumption related to the process.

2.1. Materials and alloys

As a first step, a review on PM alloys as described in literature and in technical datasheet has been performed to evaluate the consistency of the information acquired during the subsequent data gathering and to correlate the novelty of NEOHIRE alloys in comparison with existing products.

The results are shown in Table 1; results comprehend PMs adopted for different industrial applications, without narrowing the research to large electric machines typical products. According to the project definition, the typical alloys to be studied include:

- For the new bonded NEOHIRE case, the typical composition assumed for the analysis is: Neodymium (Nd) 27-28%; Iron (Fe) 71-72 %; Boron (B) 1%. This range cover part of the alloys studied in the process, while certain also include Niobium (Nb) and Gallium (Ga) (<0.5%). The peculiarities of the alloys are due to the composition close to stoichiometric value ($REE_2Fe_{14}B$) and due to the total elimination of Dysprosium (Dy), defined as Heavy-REE.

- For the reference sintered magnet, a composition comprehending Nd 30-31%; B 1%; Fe 64-69%; Dy 1%; small amount of Al, Nb, Ga has been considered. Since these alloys are not part of NEOHIRE study, a comprehensive data package being part of GaBI software has been used.

Table 1. Review on typical composition of NdFeB alloy [mass %] in comparison. Standard metal symbols are used.

Source	(Stanford Magnets, 2019)	(Binnemans et al., 2013)	(Rademaker et al., 2013)	(Zakotnik et al., 2016)	(Tharumarajah and Koltun, 2011)	Prakash et al., 2014)	(Miura et al., 2008)	(Zakotnik et al., 2008)	Hoogerstraete et al., 2014)	(International Magnaproducts, 2016)	(Xu et al., 2000)	(Milicevic et al., 2017)	(Godavarthi et al., 2015)	(Italfit Magneti, 2018)	(Bian et al., 2016)	(Wulf et al., 2017)
Nd	29 - 32	69.4	29	19.86	10	23 - 25	23.4	14	25.95	33	17 - 19	19.5	29.70 - 39.79	27 - 32	30.73	25
Fe	64.2 - 68.4	-	-	67.61	-	62 - 69	62.3	78	58.16	65	71.7 - 73.1	-	-	60 - 70	61.6	65
B	1.0 - 1.2	-	-	1.03	-	1	0.9	6	1	1.3	0.86 - 0.94	0.8	-	0.8 - 1.2	0.96	1
Dy	0.8 -1.2	5	6	3.45	-	3.5 - 5	4.1	0.6	4.21	0 - 4	5 - 5.6	2.4	-	1 - 8	-	1
Al	0.2 - 0.4	-	-	0.52	-	1 - 2	-	0.7	0.34	-	-	0.2	-	0 - 1	0.83	-
Nb	0.1 - 1	-	-	-	-	-	-	0.4	0.83	-	-	-	-	0.1 - 1	-	-
Cu	-	-	-	0.14	-	1 - 2	-	-	0.04	0.01 - 0.2	-	-	-	0.1 - 2	-	-
Co	-	-	-	0.98	-	0 - 10	3.2	-	4.22	0 - 5	-	-	3.18	0 - 4	-	2
Pr	-	23.4	-	6.12	5	0.05 - 5	-	-	0.34	0 - 5	1.81 - 1.83	4.9	5.95 - 9.96	0 - 5	4.39	6
C	-	-	-	0.08	-	0 - 0.14	-	-	0.07	-	-	1.3	-	-	-	-
O	-	-	-	0.11	-	-	5.1	-	0.41	-	-	5.6	-	-	-	-
Gd	-	2	-	-	53	1 - 2	-	-	-	-	-	-	-	-	-	-
Tb	-	0.2	-	-		-	-	-	-	-	-	-	-	-	-	-
La	-	-	-	-	5	-	-	-	-	-	-	-	-	-	-	-
Ce	-	-	-	-	9	-	-	-	-	-	-	-	-	-	-	-
Y	-	-	-	-	18	-	-	-	-	-	-	-	-	-	-	-
N	-	-	-	-	19	0 - 0.1	-	-	0.02	-		-	-	-	-	-
Ni	-	-	-	-	-	-	-	-	0.02	0.01 - 0.4	-	-	-	-	-	-
Si	-	-	-	-	-	-	-	-	0.06	-	-	-	-	-	-	-
Mn	-	-	-	-	-	-	-	-	0.05	-	-	-	-	-	-	-

2.2. Data gathering for LCI

LCI is defined as a fundamental phase involving the compilation and quantification of inputs and outputs (in terms of materials and energy) for a given product system throughout its life cycle. Data can be obtained through reports at the site, facility, and process level. The quality of the data obtained during this phase is an important point for the accuracy of the results of the whole analysis.

During NEOHIRE approach, the data gathering is carried out using an input/output approach. All the Consortium partners have been invited to compile a pre-set spreadsheet, through which two main objectives have been achieved:

- Identify with the maximum possible detail the sequence of large and small processes performed for the manufacturing of PM, starting from material acquisition phase, to alloy creation, to the formation of powders (typical form in which the material is provided for final production phase) and to the PM production

- Quantify for each process the resources used (energy, reactants, additives etc.) as inputs and the outputs such as final product amount, subproducts, waste production.

Data gathering include the definition of country origin (in order to quantify the impact of transportation from) and the description of the equipment (e.g. furnaces, press, injection molding machines) adopted for the process. Fig. 2 summarize in a graphical manner the process as a whole.

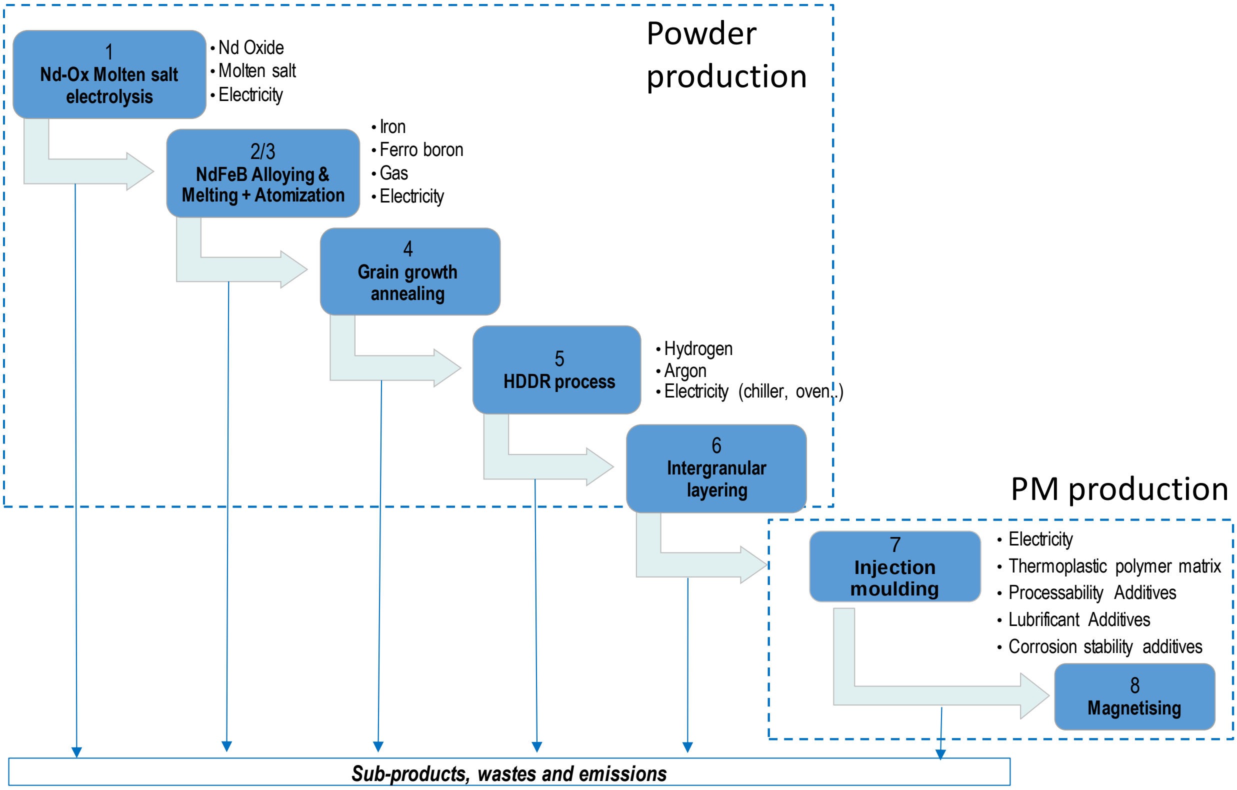

Fig. 2. Data gathering for bonded magnets: summary of the whole production process. Upper box: steps related to raw material processing, alloy creation and treatment and powder production. Lower box: production of PM starting from powder.

The main phases considered for the analysis include:

1. Production of metal-Nd starting from electrolysis of Nd-Oxide, a process which is not performed by project partners. Literature data have been adopted to directly obtain the results for the final Nd production, importing into GaBI data provided by the Critical Materials Life Cycle Assessment Tool (CMLCAT) (Arshi et al., 2018). It is assumed that Nd and REEs products are coming from China resources.
2. Alloying: during this phase, materials in metal forms are heated in a crucible up to melting point. The process is performed in a Hermiga device (Phoenix Ltd, 2018) which include all together the atomizer, next point of the list. Typical batch is 3kg.
3. Atomization: after melting point, alloy is subjected to atomization through a nozzle, while being kept in an inert atmosphere. The fall along the atomization chamber (about 1500mm, less than a large scale industrial equipment) provides the production of powders approximately ranging from 10 to over 150µm. The small size of the equipment causes that some of the powders are unsuitable for further processing due

to the “splat” phenomena (i.e. hitting the bottom of the chamber before being solified, thus resulting in non-spherical parts). Data regarding step 2 and 3 come from experimental use and have been precisely specified during data gathering.

4. Grain growth annealing: this step includes a heat treatment lasting for many hours (up to 100h) which improves material characteristics for subsequent treatments through growth of large grains
5. HDDR: the Hydrogen decrepitation deabsorbation recombination is a treatment consisting in the combined action of heating and H_2 atmosphere, which results in grain modification obtaining fine structure and an anisotropic structure (since fracture occur on preferential lines)
6. Intergranular layering: during this step, the NdFeB powder is subjected to intense heating while in presence of another other alloy, which provide surface protection for the powders.
7. Prepared powders are injected in final shape (e.g. directly in the cavities of machine rotor or in appropriate die) together with the binding polymer (e.g. PPS). Bonded PM use approximately 90% mass alloy, 10% polymer.
8. PMs are finally prepared for use through magnetization process.

Notably, the recycling process of Bonded PMs, if performed through polymer removal through solvent, is potentially able to recovery the originally formed powders which were used for injection moulding; therefore, such extracted products could be suitable for direct reuse starting from the bottom of the process (point 6), thus enabling a relevant saving of energy due to the preservation of all the treatment applied on the alloy and of its quality. For comparison, sintered PMs recycling (which includes different but comparable treatments from what shown here, from alloy formation to powder creation) necessarily requires the reprocessing of alloy as scrap.

2.3. A furnace model for heat treatments energy assessment

For all the different alloy proposal at least three different heat treatment are necessary (grain growth, HDDR, intergranular layering); since target temperature is above 800° C in all the cases, the energy consumption related to these phases is certainly relevant for the analysis. As a consequence, the results of the whole LCA are sensitive to such data.

In particular, the grain growth duration is about 100 hours, so that a significant amount of energy is consumed during this phase. Its determination depends on various conditions, such as:

- the process adopted
    - closed furnaces: each cycle starts when loading the batch of material into the furnace, which is closed and then unloaded at the end of the cycle
    - continuous furnaces: in case of industrial processes, high productivity can be obtained loading the material on a conveyor belt which transports the material through the furnace (Kruzhanov and Arnhold, 2012), built as a “tunnel”; since certain open inlet and outlet areas are necessary, the efficiency is not optimal
- the furnace adopted:
    - depending on the construction of the device, the energy consumption can vary for a same size and usable temperature depending on the insulation capabilities
    - the size of the furnace itself, for a same technology, determines the efficiency of the process due to the different surface to volume ratio; the first being mostly related to the energy loss (increasing with a power of 2 in relation to dimension) and the second being related to the acceptable load of the furnace (increasing with a power of 3 in relation to dimension)
- the conditions of use of the same furnace
    - mass introduced in the usable volume (partial or full saturation of machine capability for each batch)
    - duration of the cycle; depending on the thermal capacity of the machine, in fact, the duration and the energy consumption of the heat-up phase of the furnace can be comparable with the cycle itself (e.g. for the furnace described later in this document, 45 minutes are declared for heat-up, the energy consumption of this phase being almost negligible for a 100h cycle but relevant for a

1h cycle)

NEOHIRE partners have being working on small-scale processes and devices. The consumption of the furnaces used during testing and experimentation and the data related to such processes have been acquired in detail, however it is possible that such values are not representative of the process applied at industrial scale. At least three scenarios can be described:

1. Experimental/sample production scale: using small machines usually available in laboratory, sample having reduced mass (e.g. 0.1kg) have been produced during NEOHIRE activities. Such scale is particularly appropriate for testing new processes and materials, but the drawback is that the energy consumption per kg of material is expected to be particularly high. Preliminary data confirms this assumption; since average power for the annealing phase is in the range of 60 kW/kg.
2. Laboratory/small production scale: the use of machines able to process a few kilograms of material per cycle enables the production of the amount of powders necessary for the preparation of full size PM units samples. Even if such scale still differs from of an industrial or mass-market production, it is representative of special material production. In NEOHIRE, the reference machine suggested by partners is a 30 litres furnace (able to process up to 10kg per batch) which is filled at 25% of its capacity (2.5 kg). Considering this assumption, and using the model described below, the power consumption falls to about 2.1 kWh/kg per each hour of treatment.
3. Industrial production scale: using optimized machines and process with a relevant fill factor, the scale – up to industrial process is expected to determine a further reduction of energy consumption. Experiences in literature for similar processes (Kruzhanov and Arnhold, 2012), which describe a thermal process involving about 1h treatment at 1100° C, confirm the difficulties in assessing precisely the amount of energy use. For a same treatment, in fact, the energy use varies from 1.4 to 2.6 kWh/kg between two industrial plants.

A comparison for the first 2 scenarios described, including the results from simulation obtained by the model described as follows (defined as "hypothesis") are reported in Table 2.

Table 2. Scenarios for NEOHIRE heat treatment processes.

		Scenario 1 - Experimental systems				Scenario 2 - Laboratory/small production scale			
Process		Atomization	Grain growth annealing	HDDR	Intergranular Layering	Atomization	Grain growth annealing	HDDR	Intergranular Layering
Quantity (input)	kg	3	0.1	3.0	1.04	3	2.5	3.00	1.04
Quantity (output)	kg	2.85	0.1	2.99	1.04	2.85	2.5	2.99	1.04
Duration	h	2.25	100.0	6.75	1.0	2.25	100.0	6.75	1.00
Temperature	° C	1500	1100	780-840	800	1500	1100	780-840	800
Notes (simplified)		Hermiga equipment	Sample scale	Tube furnace	Sample scale	Hermiga equipment	Hypothesis: Carbolite RHF15/35	Tube furnace	Hypothesis: Carbolite RHF15/35 or MRF 30634
Estimated Electric Energy	MJ	180	2160.0	450.6	414.0	180	1890.0	450.6	43.3
Estimated Electric Energy per unit	MJ/kg	63.2	21600.0	150.7	398.1	63.2	756.00	150.7	41.6
Estimated average power	kW/kg	7.8	60.0	2.1	106.3	7.8	2.10	2.07	11.12

Considering the needs of the latest phase of NEOHIRE, which includes the definition of the process for the production of full-scale magnets (scenario 2 or even a larger scale one), a tool for the estimation of the energy consumed during heat treatment phases has been developed. It consists of a furnace model which has the following requirements:

- Machine scalability: various furnace size and types should be represented by the model changing its geometry and insulation data. Parametric models adaptable to various alternatives are therefore necessary.
- Load scalability: the model should be adaptable to the amount of powder and materials loaded into it
- Applicability to various thermal cycles: the model should accept the time-temperature cycle as input; the needed power is therefore going to be obtained using a temperature-based controller.

Considering that the aim of the model is to assess a suitable order of magnitude for energy consumption in order to be representative of a “class” of treatment instead of a “specific” process, an approach based on lumped elements has been adopted. Detailed Finite Element models, even if capable of high precision results, have not being considered, since their definition requires the description of a detailed geometry and any adaptation is time-intensive.

The lumped parameters model has been implemented in Matlab-Simulink software environment using the Simscape library. The use of such physical libraries, comparable within a certain extent with the well-known Modelica ones (Zupančič and Sodja, 2013), responds to the requirements above described. Main advantages of such choice, considering the context of application, are:

- possibility to solve various physical problems in the same environment (thermal, electrical, mechanical)
- graphical-based programming which simplifies debugging, model modification and expansion
- scripting features for model definition, data definition and post-processing
- easy interfacing to Simulink standard libraries for the definition of any control system.

An example furnace model as built for the NEOHIRE energy assessment phase is shown in Fig. 3. The model is simplified for figure readability; the number of lumped parameters included in the final model is larger, as described in Table 3. The volume of the furnace (as visible in Fig. 4), in fact, is represented by an array of “shells”, each one corresponding to a thermal mass (depending on shell mass and material thermal capacity) and a thermal resistor (depending on the conductivity of the material, which as a function of the temperature, and on the surface). Two arrays of shells are used to differentiate, if needed, fixed wall thickness to door thickness. Fig. 5 is an extract of the full model, in which the array of thermal masses corresponding to the shells are visible. Fig. 6 represents the temperature controller, which sets the power to be applied on the furnace; if needed, it can be set in such a way that the timer of the process is started only after heat-up phase has been completed, thus stopping the simulation only after the achievement of the real target objectives (e.g. for 1100° C treatment for 60 minutes, the model computes both heat up and cycle treatment data, final duration being about 90-100 minutes).

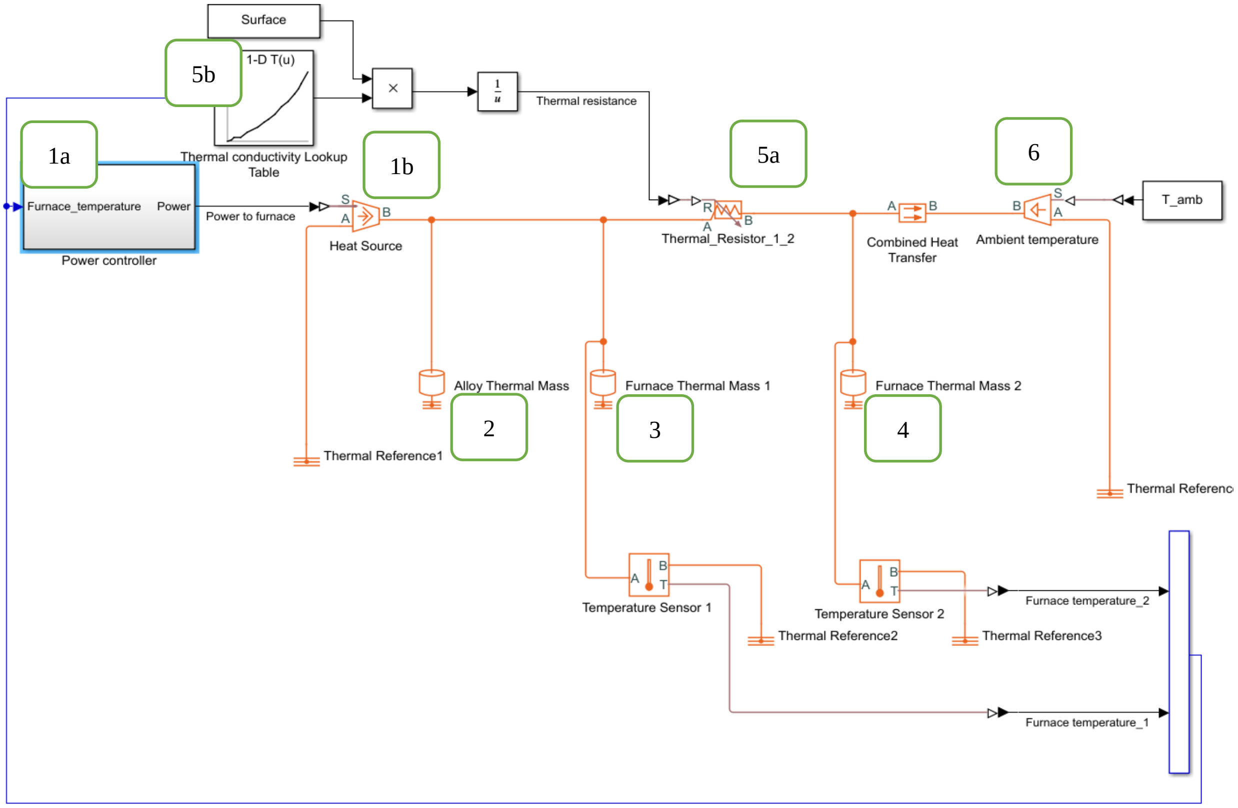

Fig. 3. Simplified lumped model of the whole Furnace. Numbered elements are described in Table 3.

Table 3. Definition of furnace elements as indicated in Fig. 3.

Number	Description	Note
1a	Power controller: compute the power required to maintain the temperature of the furnace within the target	PI controller (see Fig. 6)
1b	Heat source (ideal): applies power to the subsequent elements	
2	Alloy thermal mass: corresponds to the material batch in the furnaces	
3	Furnace thermal mass 1: corresponds to the interior walls of the furnace (high temperature, high density refractory materials)	1 mass represented for simplicity. Full model includes an array of thermal mass: 10 nodes for the fixed walls, 5 nodes for the door nodes, which have a different thickness. See Fig. 4 and Fig. 5.
4	Furnace thermal mass 2: corresponds to the interior walls of the furnace (low density insulation materials)	1 mass represented for simplicity. Full model includes an array of thermal mass: 5 nodes for the fixed walls, 5 nodes for the door nodes, which have a different thickness.
5a	Thermal resistor: corresponds to internal conduction between shells.	It is the reciprocal of Conductivity*Surface/thickness. Its unit is therefore K/W
5b	Thermal resistance calculator.	The conductivity is a function of temperature. A look-up table based on refractory material datasheet is used.
6	Power loss to the environment (ambient temperature)	Represented by a unique combined heat transfer unit.

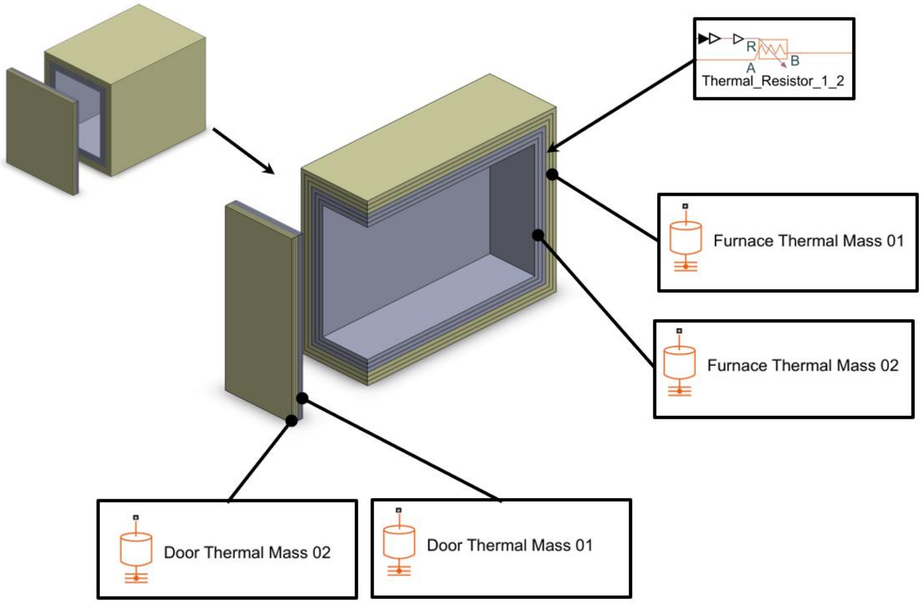

Fig. 4. From geometry to lumped parameters. Each thermal mass corresponds to a "shell" portion of the furnace walls, thickness varying with input geometry (the thickness of the most interior shell, however, is fixed at 5mm). Between each shell a resistor is used to represent thermal conduction. The two colors highlight that 2 different materials are installed (high density refractory for the interior shells, low density insulation for the outer shells). A separate group of thermal masses represents furnace door, since movable walls, in general, can differ from fixed walls. The shells correspond to a thermal masses array (see Fig. 5).

The calculation performed by the model is described in the form of flow-chart in Fig. 7, which is in accordance with similar literature exempla (Kang and Recker, 2009). A variable step solver is adopted, since it is particularly suitable for the phenomena under study. In particular, simulation step varies from about 10^{-3}- 10^{-2} s at the beginning of the simulation (high gradients of temperature for transient phases) to about 10 - 100 s in steady phases. The model is therefore not calculation-intensive and 100h treatments can be calculated in a few minutes on a regular office machine.

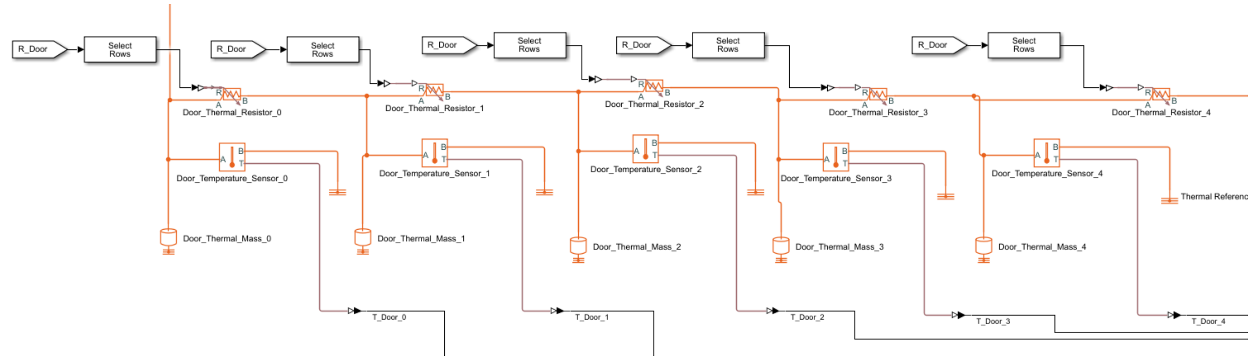

Fig. 5. Portion of the full model. Array of thermal masses used to represent the interior insulation of furnace Door surface.

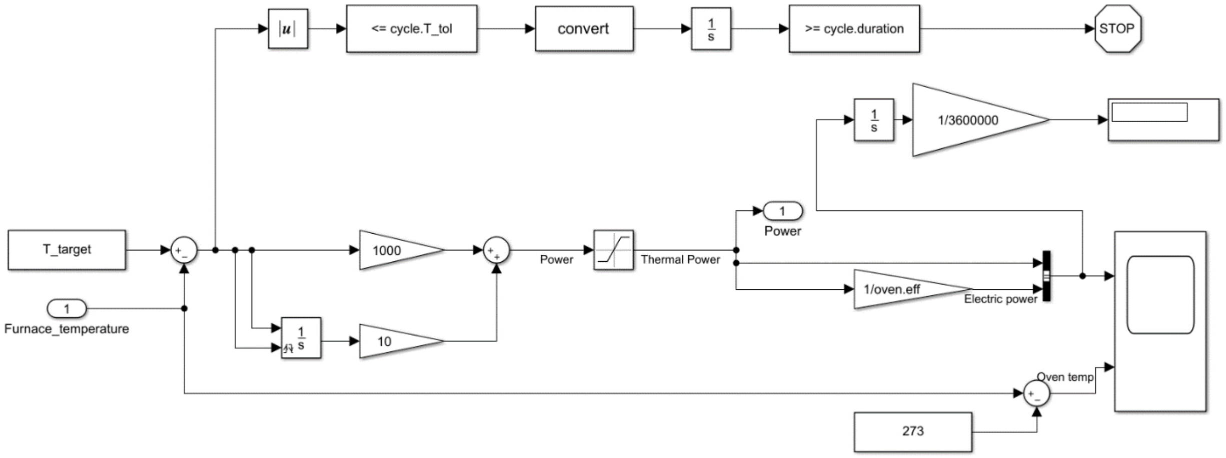

Fig. 6. Furnace power controller based on estimated Temperature in respect of cycle target temperature. If needed, pre-heating of the furnace can be calculated starting the timer only after target temperature has been reached.

The simplifications of the model have been done in order to be “conservative”, i.e., for LCA needs, leading to an overestimation of energy consumption rather than to an underestimation. The known limitations – considered acceptable for the detail required in such phase – are:

- distortions at the edges of the furnace surface shells are not considered
- it is assumed that the whole interior door surface is subjected to the maximum temperature, even if part of it is in reality in contact with the fixed walls of the furnaces
- the external temperature of the outer shell is equal to ambient temperature, thus overestimating thermal losses (usually, due to the limitations of air convection and irradiation the outer temperature of a furnace can significantly be above ambient temperature – e.g. 50° C)
- it is assumed that the temperature of the material (alloy) inside the furnace is the same of the most interior shell of the furnace; it means high thermal exchange from power source (electric resistor) to the furnace, in any case leading to an overestimation of power consumption
- Energy consumption eventually related to the modification of the material subjected to heat treatment are not considered, but – potentially – can be implemented in the model due to the flexibility of the simulation environment adopted.

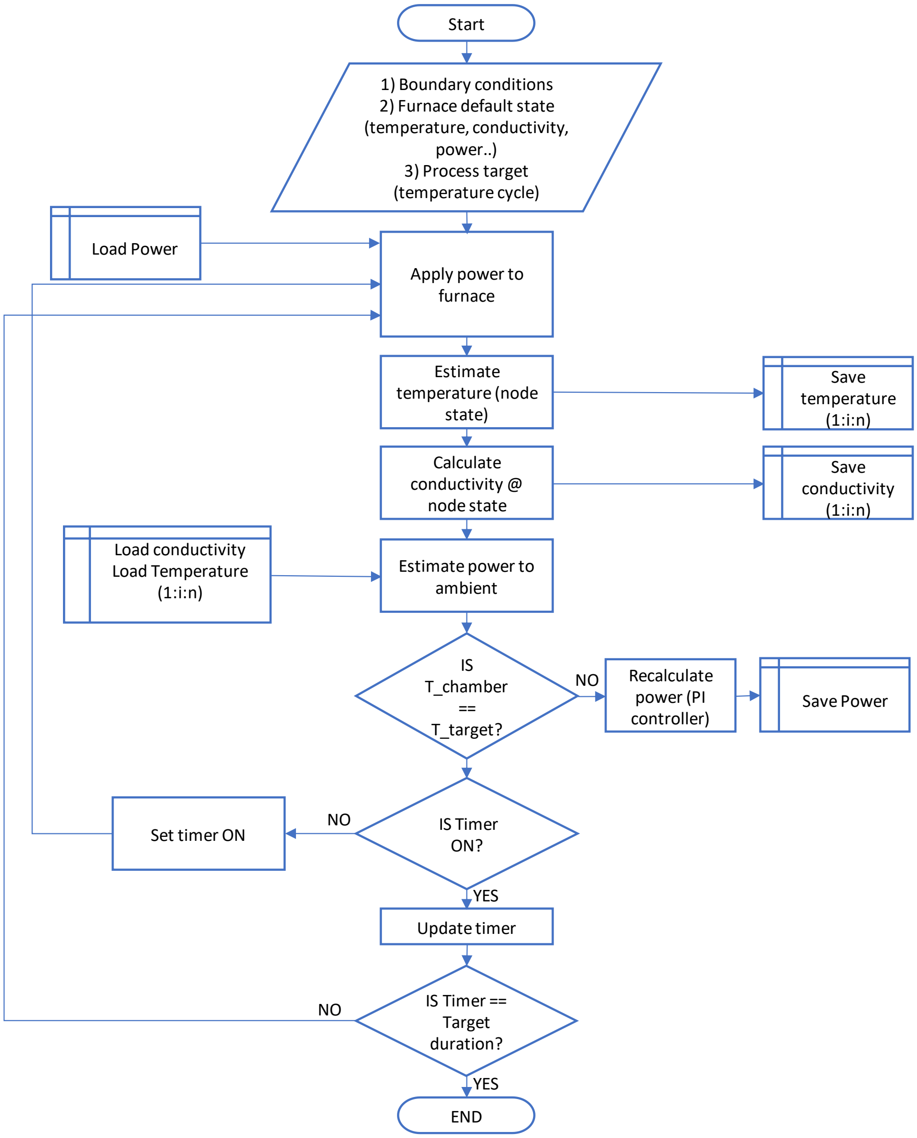

Fig. 7. Flowchart representing the calculation process implemented in the model. The note (1:i:n) means “for all the elements of the array, from 1 to n-th elements”.

Finally, the model has been calibrated on the reference furnace adopted for scenario (CARBOLITE 15/35), whose characteristics are:

- Maximum temperature: 1500° C
- Usable chamber Height x Width x Depth: 250 x 300 x 465 (mm)
- Heat up time to 1400° C: 46 mins
- Maximum power: 16 kW
- Holding power at 1400° C: 6200 W
- Weight: 178 kg
- Door: light (visible in datasheet picture)
- Volume: 35 l

The calibration has been done according to the following criteria:

1. Equivalence of heat-up time
2. Equivalence of holding power
3. Equivalence of the mass of the refractory/insulation system, assuming that about 50% of the furnace (90kg) is related to refractory and insulation materials (the remaining mass being due to thermal resistors, metal structure, converter etc.).

The calibration steps of the model have been:

1. Selection of refractory/insulators within commercial materials
2. Application on the model and first attempt thickness
3. Run of the model
4. Iterative modification of thickness of the two materials until equivalence is satisfied
    a. Interior thermal masses are mainly influencing weight and heat-up time due to the high density of refractory materials
    b. Outer thermal masses are mainly influencing holding power

For the selection of the material, assuming good design procedures for industrial furnaces (Brunklaus, 1975), a high density one (Morgan advanced materials, 2019) has been used for the interior surface, while a low density ceramic wool has been used for the outer one. Literature data confirms that the value adopted from the catalog are effectively comparable with up-to-date refractory materials (Sadik et al., 2014). The characteristics of the selected materials are summarized in Table 4 and Fig. 8.

Table 4. Materials selected for the furnace.

Characteristics	Interior (Material 1)	Outer (Material 2)
Type	Structural Insulating Firebrick JM-30 HD	Refractory Ceramic Fibre – Kaowool 3000 paper
Continuous use Max temperature ° C	1650° C	1538° C
Density kg/m^3	1190	160
Thermal Conductivity, W/m*K	0.47 @ 400° C 0.51 @ 1200° C	0.049 @ 200° C 0.32 @ 1538° C
Specific Heat capacity kJ/kg*K	1100	1100

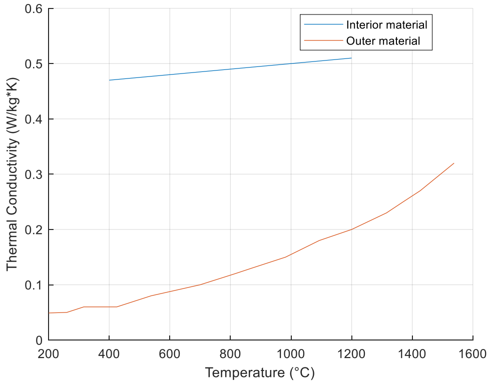

Fig. 8. Thermal conductivity of the materials selected for the furnace model. For the interior material, conductivity above declared values will be linearly extrapolated by the model.

After the preliminary preparation and selection of material above described, the system has been calibrated considering the hypotheses explained in Table 5. Considering the results listed in the table, the approximation of the model is considered sufficiently representative for the energy assessment needed for LCA analysis. Simulated furnace performances are shown in Fig. 9.

Table 5. Parameters, boundary conditions and main results resulting after model calibration.

Characteristics	Furnace model	Furnace datasheet
Thickness of material 1	Furnace walls: 65mm Door wall: 30mm	Not declared
Thickness of material 2	Furnace walls: 35mm Door wall: 10mm	Not declared
Total mass of insulation system	76.1 kg	Not declared – hypothesis: 50% of total mass (89kg)
Power	16.000 W (electric) 15.200 W (thermal power considering 95% efficiency of the system)	16.000 W (electric)
Heat up time (initial temperature: 20° C)	1340° C @ 46 minutes from start 1400° C @ 51.5 miuntes from start	1400° C @ 46 minutes from start
Holding power @1400 C°	6190 W (stationary condition achieved approximately after 6 hours)	6200 W
Notes	Additional +25% surface added at door model to represent gasket losses	

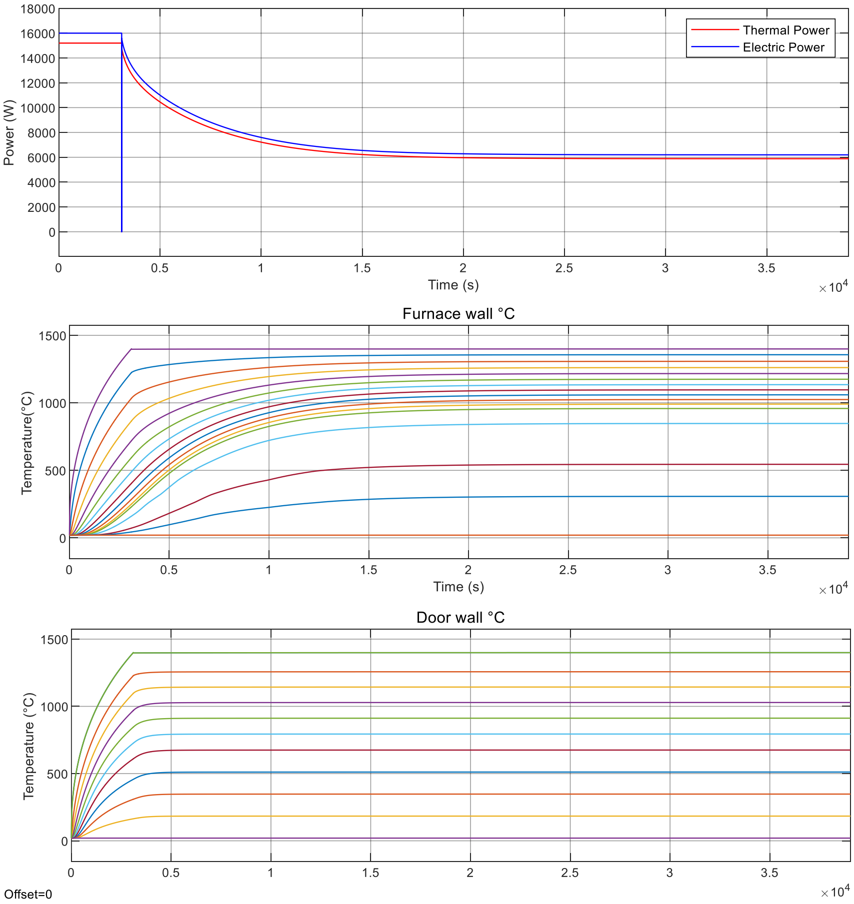

Fig. 9. Results from the simulation used for model calibration.

3. Environmental analysis (LCA) results

The environmental results are carried out by the ILCD/PEF method included in GaBi software tool.

The International Reference Life Cycle Data System (ILCD) provides a common basis for consistent, robust and quality-assured life cycle data and studies. Such data and studies support coherent SCP instruments, such as Ecolabelling, Eco-design, Carbon footprinting, and Green Public Procurement.

Within the ILCD Handbook, 14 methods were recommended for impact assessment in LCA; the Product Environmental Footprint (PEF) builds on these recommendations (Sala et al., 2015).

The choice to use ILCD/PEF is twofold.

- the recommended models and characterisation factors are the result of a scientifically sound and robust study
- Secondly, the lacking processes for the bonded magnet have been integrated through the corresponding results generated from the CMLCAT tool (Arshi et al., 2018), since it uses the ILCD/PEF and TRACI methods.

The adopted impact categories of ILCD/PEF method are listed in Table 6.

Table 6. ILCD/PEF impact categories (v. 1.09).

Impact category	Unit
Acidification midpoint	[Mole of H+ eq.]
Climate change midpoint, excl biogenic carbon	[kg CO2-Equiv.]
Climate change midpoint, incl biogenic carbon	[kg CO2-Equiv.]
Ecotoxicity freshwater midpoint	[CTUe]
Eutrophication freshwater midpoint	[kg P eq]
Eutrophication marine midpoint	[kg N-Equiv.]
Eutrophication terrestrial midpoint	[Mole of N eq.]
Human toxicity midpoint, cancer effects	[CTUh]
Human toxicity midpoint, non-cancer effects	[CTUh]
Ionizing radiation midpoint, human health	[kBq U235 eq]
Land use midpoint	[kg C deficit eq.]
Ozone depletion midpoint	[kg CFC-11 eq]
Particulate matter/Respiratory inorganics midpoint	[kg PM2,5-Equiv.]
Photochemical ozone formation midpoint, human health	[kg NMVOC]
Resource depletion water, midpoint [m^3 eq.]	[m^3 eq.]

3.1. Results of analysis

Results here presented compare the reference PM (sintered ones) with NEOHIRE bonded PM. The missing information for the sintered PM solution have been completed by the commercial process datasets “Magnet Nd-Fe-Dy-B; sintered magnet process”, implemented in GaBI (Thinkstep, 2019). However, it is an aggregated process; this means that it is not possible to define the contributions for each process but only the final LCA result for the sintered solution.

For bonded PMs, since the process has been modeled in detail, the percentage of impact related to each single phase can be determined. The results of the 2 scenarios proposed are shown in Table 7.

The first observation is that, looking at all the categories, the scenario 1 for bonded magnet production (small laboratory scale, i.e. few grams of metal per batch) is, as expected, by far above the impact of the reference sintered PM (valid for industrial process); therefore, a scale-up proposal for the process has to be considered to provide a significative comparison.

On the other hand, the scenario 2 for bonded magnets, while providing impacts which are significantly higher than reference one, shows that the assessment of energy impact is particularly critical for the significance of the analysis. Looking at Fig. 10, the most relevant impact is related to material supply and atomization, a process for which an up-scaling hypothesis still has to be formulated. This latter observation can explain the reason for the difference between sintered PM and bonded PM – scenario 2 impact.

As said, however, the preliminary LCA presented is still under development and does not implement 2 factors potentially affecting results in a significant manner:

1. Recycling still has to be considered, a procedure which could extend the life of PM powders for more generation of products, thus reducing significantly the impact per each re-generation of the magnets
2. Bonded magnets enable optimization of generators in such a way that a smaller amount of PM installed per machine is expected in comparison with sintered ones. Therefore, results have to be analyzed on the basis of the final FU (kW_{REEs} /MW, as said).

Table 7. Preliminary results of LCA analysis considering provisional scenarios. The results confirms the need for scale-up hypotheses in order to exclude Scenario 1 (laboratory scale processes) for bonded magnet, which provides data incomparable to reference scenario (sintered magnets).

Impact category	Sintered	Bonded SC. 1	Bonded SC. 2
Acidification midpoint [Mole of H+ eq.]	6,62E-01	8.12E+01	7.64E-01
Climate change midpoint. excl biogenic carbon [kg CO2 eq.]	8,99E+01	2.64E+04	1.61E+02
Climate change midpoint, incl biogenic carbon [kg CO2 eq.]	8,99E+01	2.64E+04	1.61E+02
Ecotoxicity freshwater midpoint [CTUe]	4,87E+01	9.22E+02	1.61E+02
Eutrophication freshwater midpoint [kg P eq.]	7,87E-05	8.29E-02	7.72E-03
Eutrophication marine midpoint [kg N eq.]	8,28E-02	1.65E+01	7.82E-02
Eutrophication terrestrial midpoint [Mole of N eq.]	9,14E-01	1.67E+02	1.72E+00
Human toxicity midpoint, cancer effects [CTUh]	6,60E-07	2.38E-05	2.24E-06
Human toxicity midpoint, non-cancer effects [CTUh]	1,16E-05	-1.56E-05	6.58E-06
Ionizing radiation midpoint, human health [kBq U235 eq.]	1,53E+00	1.25E+04	3.31E+01
Land use midpoint [kg C deficit eq.]	-1,33E+03	1.40E+04	7.34E+01
Ozone depletion midpoint [kg CFC-11 eq.]	2,52E-11	6.37E-06	6.25E-06
Particulate matter/Respiratory inorganics midpoint [kg PM2.5 eq.]	7,01E-02	4.00E+00	1.01E-01
Photochemical ozone formation midpoint, human health [kg NMVOC eq.]	2,53E-01	4.33E+01	4.57E-01
Resource depletion water, midpoint [m^3 eq.]	1,57E+00	1.81E+03	9.33E+00
Resource depletion, mineral, fossils and renewables, midpoint [kg Sb eq.]	3,81E-01	1.24E-01	3.49E-03

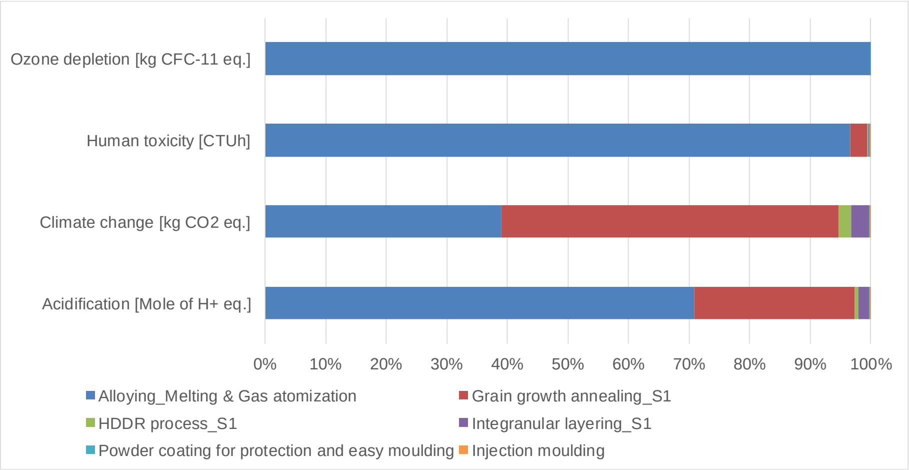

Fig. 10. Repartition of the impact per phase of PM processing (Bonded PM, scenario 2).

4. Conclusions

According to the needs of the NEOHIRE project, the development of advanced bonded PM magnets is proposed for the installation on wind turbines generators. To determine the effective advantage of the solution in comparison with reference one (i.e. sintered PMs), Life Cycle analyses have been developed. The results of such activity include a literature review on materials adopted for PM production, which shows the peculiarity of the proposed alloys.

The process has been described mapping all the steps that, starting from raw materials (Nd-Fe based alloys) lead to the production of high performance, ultra-fine, anisotropic powders to be used for bonded magnets. Looking at the data, not only the material supply phase differentiates the two solutions (bonded PMs not including Heavy REEs), but also the occurrence of heat treatments determines a significant energy consumption for the whole process, so that an investigation including all production steps is necessary.

During data gathering phase, actual data from experimental production – laboratory scale for research scopes – have been obtained, resulting in relevant impacts when LCA has been performed. To overcome the limitations of such approach and to propose a realistic scale-up procedure, a few hypotheses have been formulated to define a realistic energy consumption scenario. As a first step, a parametric model for the calculation of energy use per treatment has been constructed in a physical simulation environment, and it has been tested to represent a known case study. If the limitations related to the need of a simplified, rapid execution model, are acceptable, it is ready to be used to represent any furnace within the typology of closed ones.

Using this approach, the impact of bonded magnet production decreases of 2 order of magnitudes between the two scenarios, even if still appearing to be higher than reference PMs impact. At the current stage of the research, it is not possible to confirm if such difference is either realistic (e.g. related to the intrinsic characteristics of the process) or induced by the current limitations of the study itself.

Next steps of NEOHIRE Life Cycle related activity include: the definition of the final scenario, which should be as similar as possible to a realistic industrialization of the process; the performing of life cycle costing and social-life cycle estimations; the final scaling to the performance based Functional Unit (kg/MW of the machine, a parameter also related to machine efficiency and to its useful life), the calculation over an extended use-phase period of the powders, assuming that effective recycling will be possible. Only after the resolution of the uncertainties here presented and the consideration of all the life phase, the results of the comparison could be considered demonstrated.

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