PASSENGER Project: LCA methodologies for the conventional permanent magnets production processes

MNLT

MNLT Innovations

- **Business Development Manager**
- **PhD in Material Science**
- **Field of expertise: circular economy**

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MNLT INNOVATIONS P.C.

NAME: MNLT INNOVATIONS P.C.

CATEGORY: Small-Medium Enterprise (SME)

OFFICE BASE: Kifisias 125-127, 11524 Athens, Greece

ESTABLISHMENT: 2018

SERVICES

- **Sustainability Studies (LCA/LCC)** in the fields of **material science**, **catalysis**, **recycling** and **circular economy** of **critical raw materials**, **hydrogen technologies** and **geo/building materials**.
- Specializes in **Innovation Business Development** and **Planning**
- Provides business development services to innovative organizations and private companies for helping them to **create robust** and **sustainable businesses.**

BUSINESS DEVELOPMENT

MATERIALS SOURCING AND EXPLOITATION

PRODUCT/PROCESS AND DEVELOPMENT

LIFE CYCLE ASSESSMENT/LIFE CYCLE COST

TECHNOLOGICAL SUPPORT AND MONITORING

(NOVEL) PRODUCTS COMMERCIALISATION

Europe’s dependence on critical and scarce raw materials for permanent magnets

- The extraction and refining of rare earth elements (REEs) is one of the most energy-intensive and polluting process of all metal-extraction processes. The recycling process of REE in permanent magnets is also expensive, energy intensive and with a significant environmental impact.
- Rare earth elements are under extremely serious supply risk: they are extremely costly, subject to great price volatility, and prone to supply crises.
- REE magnets have a good magnetic performance, but they are not perfect: they decay easily, they are hard to recycle, and their efficiency decreases dramatically at elevated temperature.

We cannot aim to make the transition to a green Europe, which requires transport electrification, power generation and smart facilities, if we do not find a way to develop permanent magnets without using rare earth elements.

Permanent magnets and applications

Wind turbines

Aerospace applications

Large industrial equipment

Smartphones
HDDs
Washing machines
Elevators

PMs in motors and generators

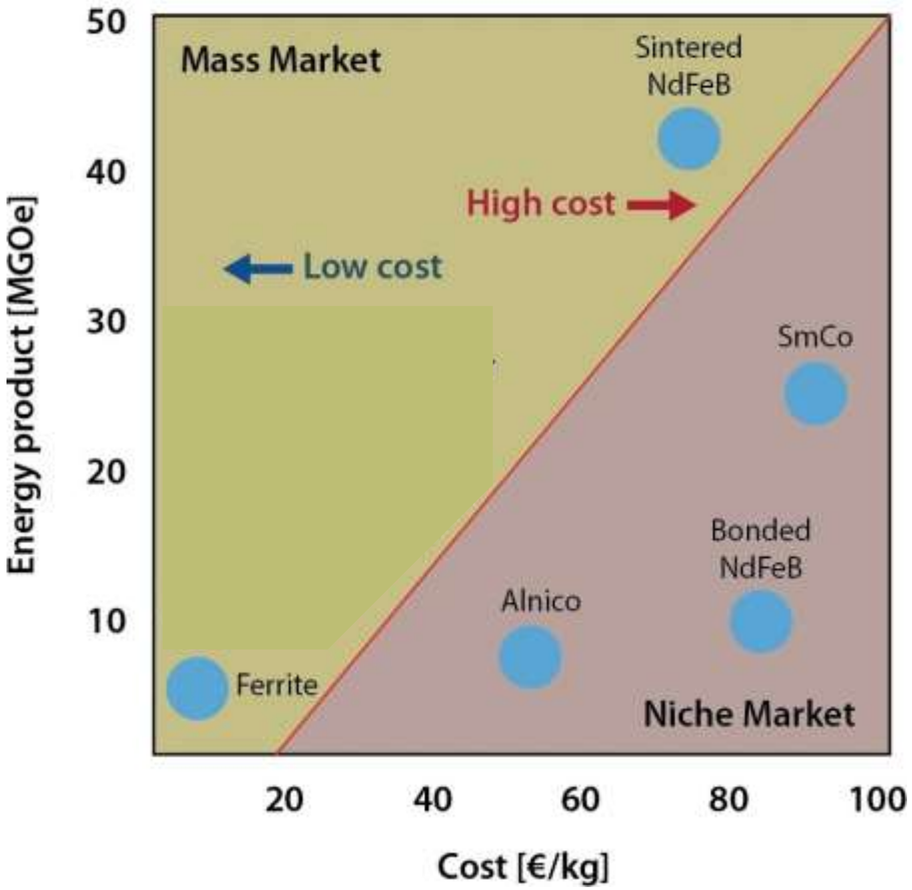
Hard disk drive

Transport
- Starter motors
- Small electric motors
- Actuators and sensors
- Dynamos

Consumer Goods, Electronics & Communication
- Microphones
- Loudspeakers
- Holding magnets
- Toys

Home appliance
- Washing machines
- Refrigerators
- Magnetron in microwave ovens
- Air conditioner

- Machine tools
- Small electric motors
- Transformers
- Actuators and sensors
- Magnetic separators



SOLUTION

MISSION

Contribute to a green, sustainable Europe by developing an alternative to raw materials in the construction of permanent magnets and testing their performance in the electromobility sector.

HOW?

PASSENGER proposes **improved strontium ferrite (Sr-ferrite)** and a **Manganese-Aluminum-Carbon (MnAlC)** alloy as a substitute to guarantee a sustainable production of permanent magnets in Europe: an alternative without critical raw elements, based on resources that are widely available in Europe, with enough research to provide a solid base for a successful transition from the lab to the industrial production in our Pilot Plants.

Challenges

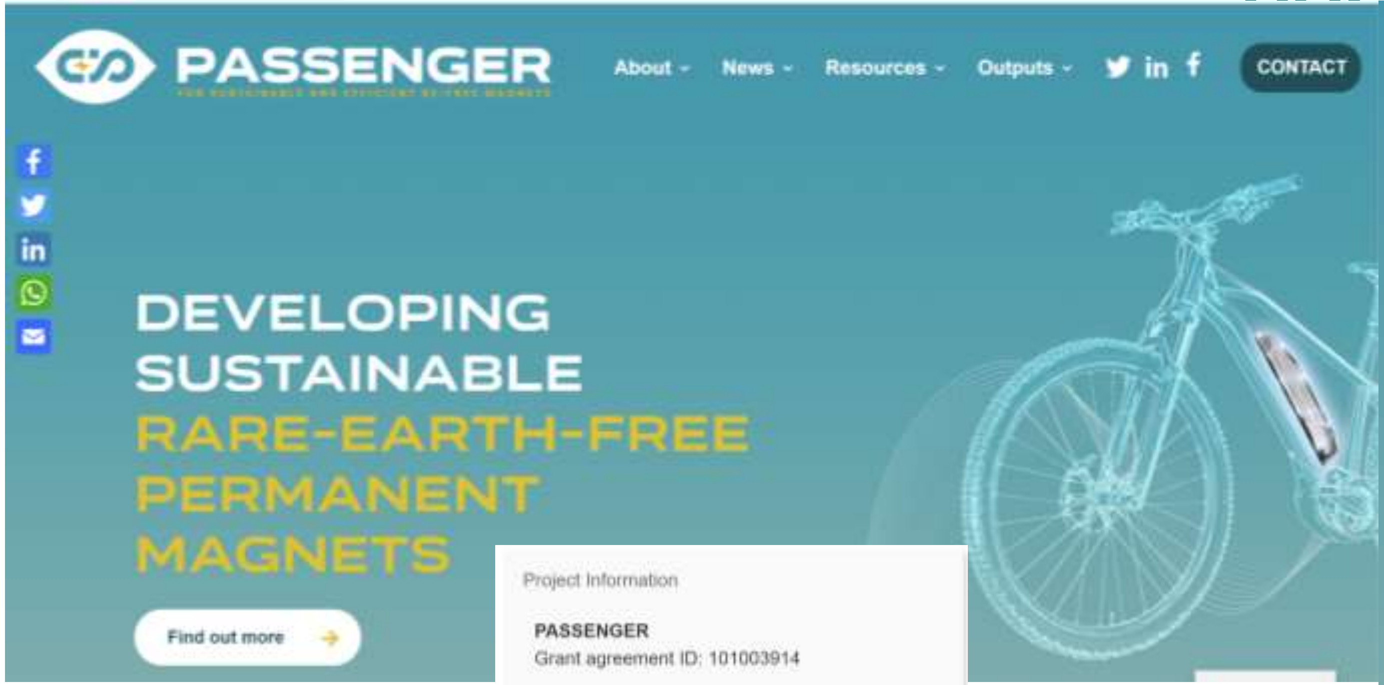
1

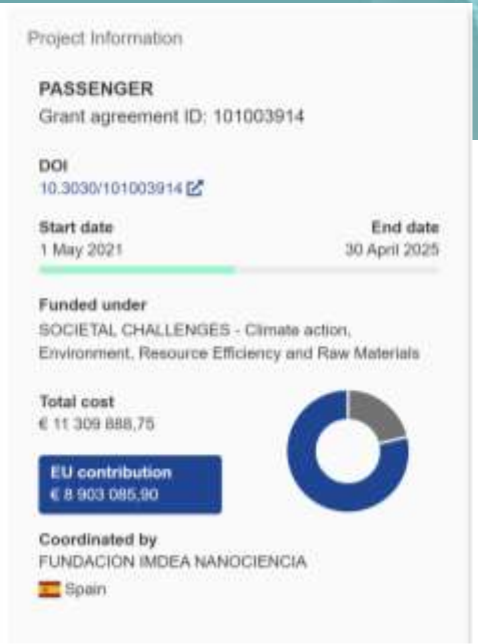
Substitution of critical raw materials to be able to produce permanent magnets with European resources.

2

Scaling up the newly developed technologies, bringing them from the lab to the market.

PASSENGER PROJECT





Project Information

PASSENGER

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DOI

10.3030/101003914

Start date	End date
1 May 2021	30 April 2025

Funded under

SOCIETAL CHALLENGES - Climate action, Environment, Resource Efficiency and Raw Materials

Total cost

€ 11 309 888,75

EU contribution

€ 8 903 085,90

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FUNDACION IMDEA NANOCIENCIA

Spain

Cost-Benefit Analysis (CBA) of Passenger magnets

Cost Structure for NdFeB Sintered Magnets: China

Material	Weight%	EUR/kg	EUR per kg of alloy	% of materials	Comments
Nd	24,2	36,96	8,94	48,2	
Pr	5	36,96	1,85	10	From NdPr
Dy	2,8	224	6,27	33,8	From Fe-Dy
SubTot	***32***		***17,06***	***92***	
Fe	64,09	0,44	0,28	1,5	Fe plus Fe-B
Co	1	31	0,31	1,7	
SubTot	***65,09***		***0,59***	***3,2***	
B	1,05	0,53	0,01	0	B from Ferro-Boron
C	0,01	0,5	0	0	
SubTot	***1,06***		***0,01***	***0***	
Al	0,3	1,77	0,01	0	
Cu	0,5	6,15	0,03	0,2	
Ga	0,5	135	0,68	3,6	
Nd	0,5	36	0,18	1	
SubTot	***1,8***		***0,89***	***4,8***	
Other	0,05				Contaminants: Mn, O, S, etc
Total	100		**18,55**	**EUR/kg**	**Material cost**
			2,4	**EUR/kg**	**Magnet manufacturing w/o materials**
			23,82	**EUR/kg**	**Magnet manufacturing with materials assuming material yield 86,6%**
			26,202	**EUR/kg**	**Magnet Selling Price with 10% selling margin**

Cost Structure for NdFeB Sintered Magnets: West

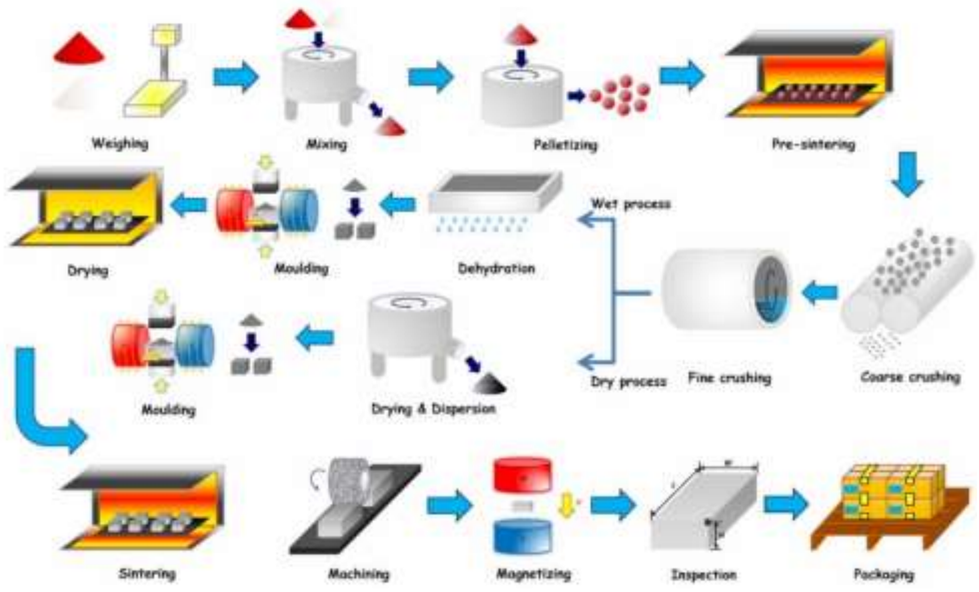
Material	Weight%	EUR/kg	EUR per kg of alloy	% of materials	Comments
Nd	24,2	47,5	11,5	49,1	
Pr	5	47,5	2,38	10,1	From NdPr
Dy	2,8	288	8,06	34,4	From Fe-Dy
SubTot	***32***		***21,4***	***93,6***	
Fe	64,09	0,44	0,28	1,2	Fe plus Fe-B
Co	1	31	0,31	1,3	
SubTot	***65,09***		***0,59***	***2,5***	
B	1,05	0,53	0,01	0	B from Ferro-Boron
C	0,01	0,5	0	0	
SubTot	***1,06***		***0,01***	***0***	
Al	0,3	1,77	0,01	0	
Cu	0,5	6,15	0,03	0,2	
Ga	0,5	135	0,68	2,9	
Nd	0,5	36	0,18	0,8	
SubTot	***1,8***		***0,89***	***3,8***	
Other	0,05				Contaminants: Mn, O, S, etc
Total	100		**22,89**	**EUR/kg**	**Material cost**
			6,71	**EUR/kg**	**Magnet manufacturing w/o materials**
			33,14	**EUR/kg**	**Magnet manufacturing with materials assuming material yield 86,6%**
			43,082	**EUR/kg**	**Magnet Selling Price with 30% selling margin**

ca 40% lower selling price

Ferrite (SrFe12O19) permanent magnets manufacturing process

(SrFe12O19) magnets

Description of the flowsheet of ferrite magnets

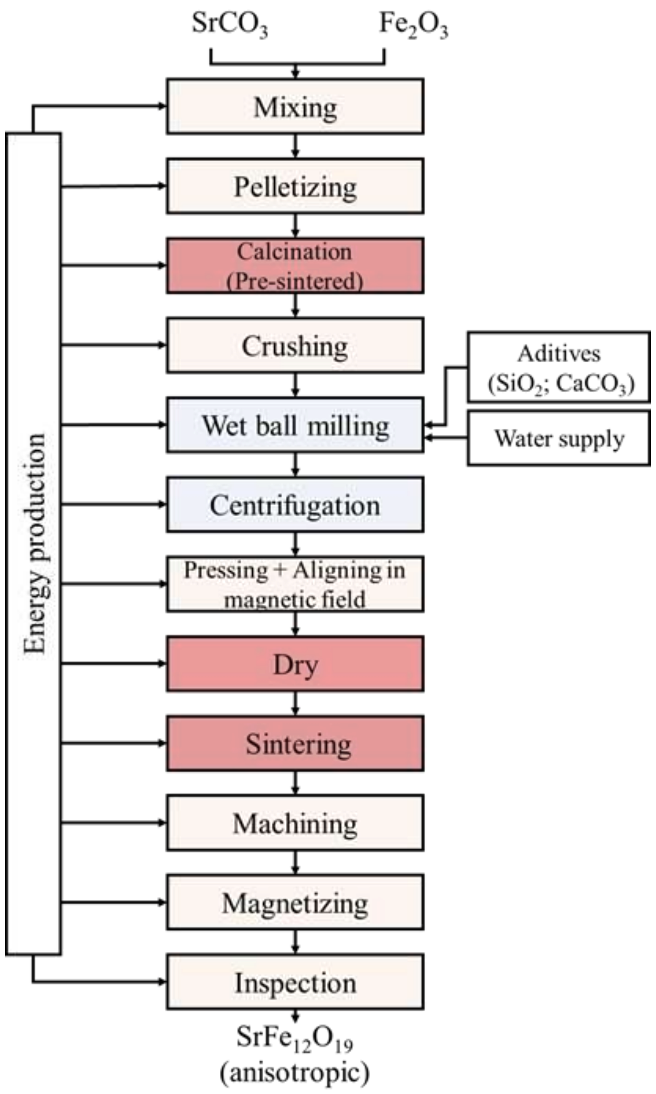


Manufacturing process of SrFe12O19 magnets

Image: https://www.magnet-sdm.com/2017/06/23/1186/

Ferrite ($SrFe_{12}O_{19}$) permanent magnet sintering route

- Process starts with the mixture of raw materials ($SrCO_3$, Fe_2O_3) followed by the pelletizing of the mixed powder.
- Pelletizing is performed to enhance the pre-sintered step which takes place in a rotatory kiln at 1250ºC for 3h to form metallic oxides. Once pellets have been calcined, the pre-sintered pellets are ground into a coarse powder of 10 µm, and then, additives and water are added to the coarse powder and subjected to a secondary ball milling to obtain a fine slurry.
- Before the molding step, the slurry is dehydrated by centrifugation to the adjust the slurry concentration in 75wt% and optimize the wet pressing. The fine slurry is molding under a pressure of 10 MPa and a DC magnetic field of 50000 A, to obtain cylinders with a diameter of 50mm and length of 10mm.
- The compact magnets are placed in an oven at 75ºC for 24h before being sintered in a wagon kiln at 1230ºC for 8h to fuse particles together and form dense solid material.
- Finally, the ferrite magnets produced are magnetized until saturation and inspected to their sale. The magnetic properties obtained in this sintering route are the following: *Br* 4.7 kG, H_c 3 kOe and $(BH)_{max}$ 4.4 MGOe.



Ferrite permanent magnet sintering route.

Magnetic properties of ferrite permanent magnet

Magnetic saturation **(Ms)**: The point beyond which magnetic flux density in a magnetic core does not increase with an increase of MMF (NI) called the magnetic saturation of the core.

Magnetic remanence **(Mr)**:Remanence or remanent magnetization or residual magnetism is the magnetization left behind in a ferromagnetic material (such as iron) after an external magnetic field is removed.

Coercivity **(H_C)**: A measure of the ability of a ferromagnetic material to withstand an external magnetic field without becoming demagnetized.

Maximum energy product **$(BH)_{max}$**: Important figure-of-merit for the strength of a permanent magnet material.

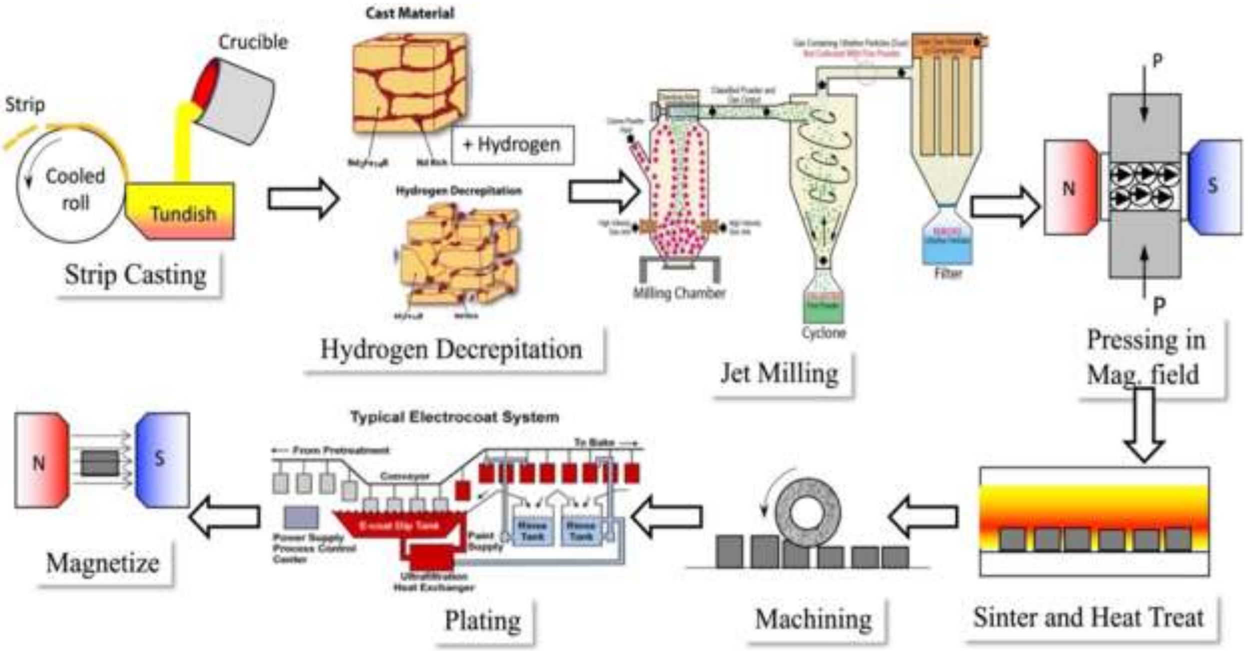
Composition	Sintering technique	Ms [emu g⁻¹]	Mr [emu g⁻¹] (Mr) [T]	Hc [kOe]	$(BH)_{max}$ [MGOe]
$SrFe_{12}O_{19}$	Conventional (Thermal sintering)		(0.38)	3.40	4.21
$SrFe_{12}O_{19}$ · SiO_2	Conventional (Thermal sintering)	54		1.70	
$SrFe_{12}O_{19}$· 0.2%PVA·0,6%SiO_2	Ceramic processing route with two-step sintering	58	46	2.05	
$SrFe_{12}O_{19}$	Microwave-assisted calcination route	54.8	29.52	5.30	
$SrFe_{12}O_{19}$	Microwave sintering	50.4		5.50	
M- $SrFe_{12}O_{19}$	Microwave sintering	64		1.20	
SrM ferrite fine particles (1.0%La_2O_3.0.1%Co_3O_4)	Spark Plasma sintering		(0.32)	4.10	2.29
$SrFe_{12}O_{19}$	Spark Plasma sintering	73.6	65.8	2.10	2.75
$SrFe_{12}O_{19}$	Hydrothermal: Sol-gel precursor coating technique	64.5		4.90	
$SrFe_{12}O_{19}$	Hydrothermal	72.2	44.76	2.20	1.20

Most common techniques and the related magnetic properties

MnAlC permanent magnet sintering route

MnAlC and Nd-Fe-B

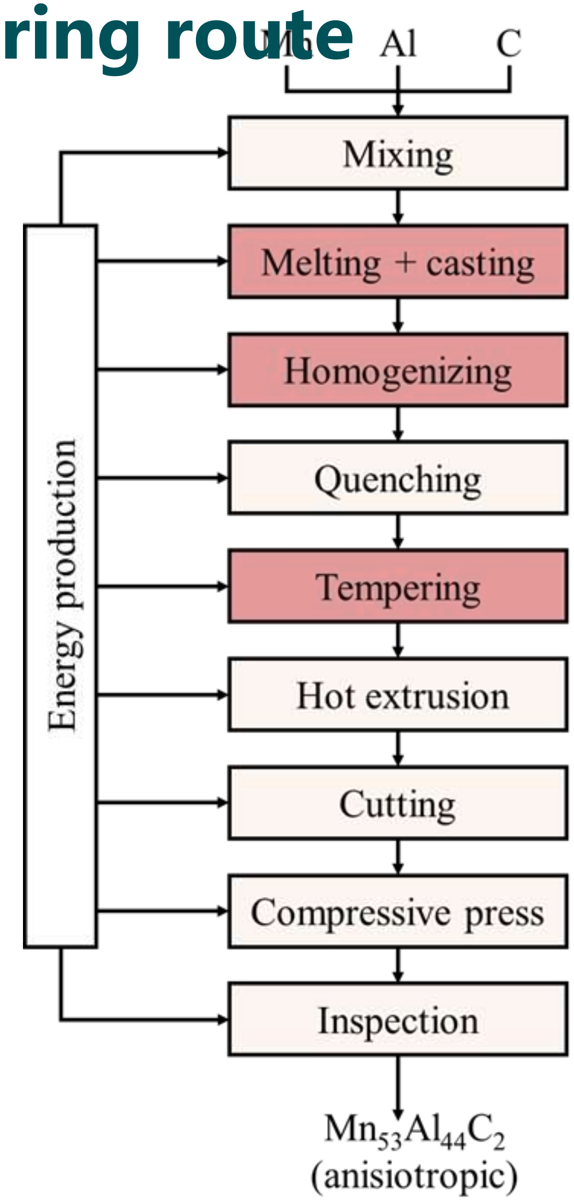
Description of the flowsheet of Nd-Fe-B and MnAlC magnets



Basic process steps for the Nd-Fe-B-based magnets

MnAlC permanent magnet sintering route

- MnAlC permanent magnet is produced by a casting/hot extrusion method
- After melting the pure element in an induction furnace at 1400ºC, the molten mixture consisting of 70%w/w Mn, 29.5%w/w Al and 0.5%w/w C is molded into the shape of cylinders with 40 mm in diameter and 30 mm in heigh.
- The ingots are homogenized at 1100ºC for 2 hours to obtain the MnAlC-ε phase, followed by air quenching and tempering at 600ºC for 20 min to promote the ε→τ phase transformation.
- The tempered pieces are extruded at 720ºC with a pressure of 780 MPa to a diameter of 15 mm causing a final ingot long of 220 mm.
- Thereafter, each ingot is cut into pieces with a thickness of 20 mm to be subjected to free compressive working, reducing 20% the heigh of the cylinders.
- The final sintered Mn53Al45C2 permanent magnets, with a dimension of 15 mm in diameter and 16 mm in height, have the following magnetic characteristics: Br 4.7 kGs, Hc 3 kOe and (BH)max 4.4 MGOe



MnAlC permanent magnet sintering route.

Magnetic properties of MnAlC bulk magnet

Magnetic saturation **(Ms):** The point beyond which magnetic flux density in a magnetic core does not increase with an increase of MMF (NI) called the magnetic saturation of the core.

Magnetic remanence **(Mr):** Remanence or remanent magnetization or residual magnetism is the magnetization left behind in a ferromagnetic material (such as iron) after an external magnetic field is removed.

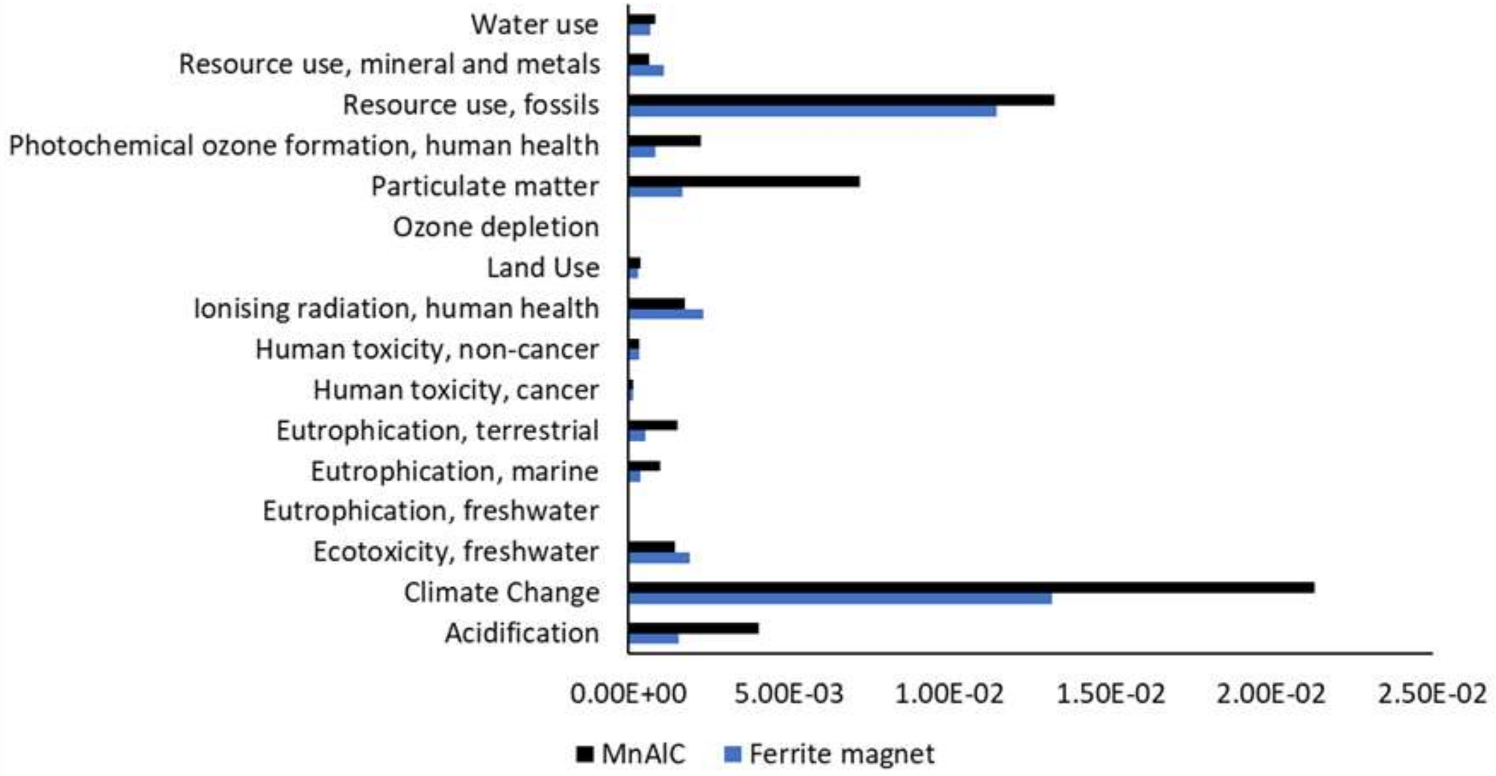
Coercivity **(H_C):** A measure of the ability of a ferromagnetic material to withstand an external magnetic field without becoming demagnetized.

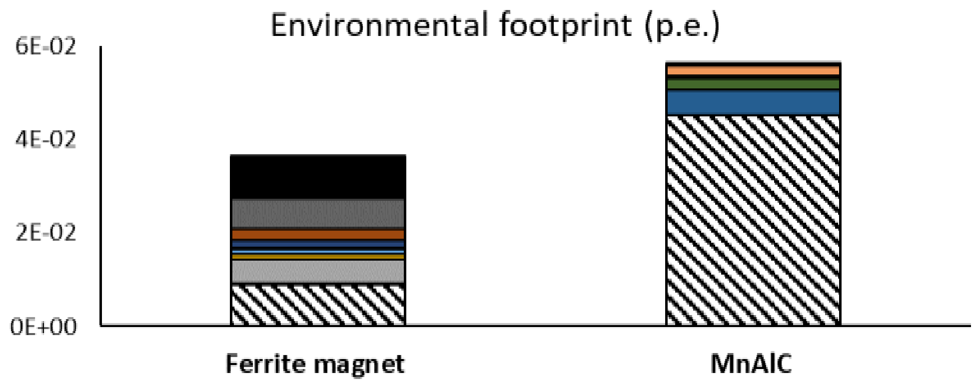
Maximum energy product **$(BH)_{max}$:** Important figure-of-merit for the strength of a permanent magnet material.

Composition	Sintering technique	Ms [emu g^{-1}] (Ms) [T]	Mr [emu g^{-1}] (Ms) [T]	Hc [kOe]	$(BH)_{max}$ [MGOe]
$Mn_{53}Al_{45}C_2$	Casting + Annealing + Hot extrusion		(0.61)	2.70	6.16
$Mn_{55}Al_{45}C_1$	Mechanical milling + powder compaction + Annealing	119	41	1.50	0.78
$Mn_{56}Al_{44}$	Mechanical milling + Spark Plasma Sintering + Rapid thermal annealing	28		2.43	
$Mn_{53.5}Al_{44.5}C2$	Art-melting + Annealing + High energy ball milling + Hot compaction	(0.50)	(0.28)	3.30	0.60
$Mn_{53.5}Al_{44.5}C2$	Art-melting + Annealing + High energy ball milling + Microwave sintering + Compaction	94	39	1.10	0.50
$(Mn_{54}Al_{46})_{97.56}C_{2.44}$	Gas atomization powdering + annealing + Compaction	90	39	3.40	
MnAlC	Gas atomization powdering+ Annealing + Hot compaction	77	42.3	3.61	1.38
$(Mn_{54}Al_{46})_{97.56}C_{2.44}$	Melting + Melt-spinning + Annealing + Crushing + Compation	122		1.30	
$Mn_{54}Al_{44}C_2$	Melting + Melt-spinning + Mechanical milling + Spark Plama Sintering	(0.55)	(0.31)	1.80	

Most common techniques and the related magnetic properties of MnAlC bulk magnet

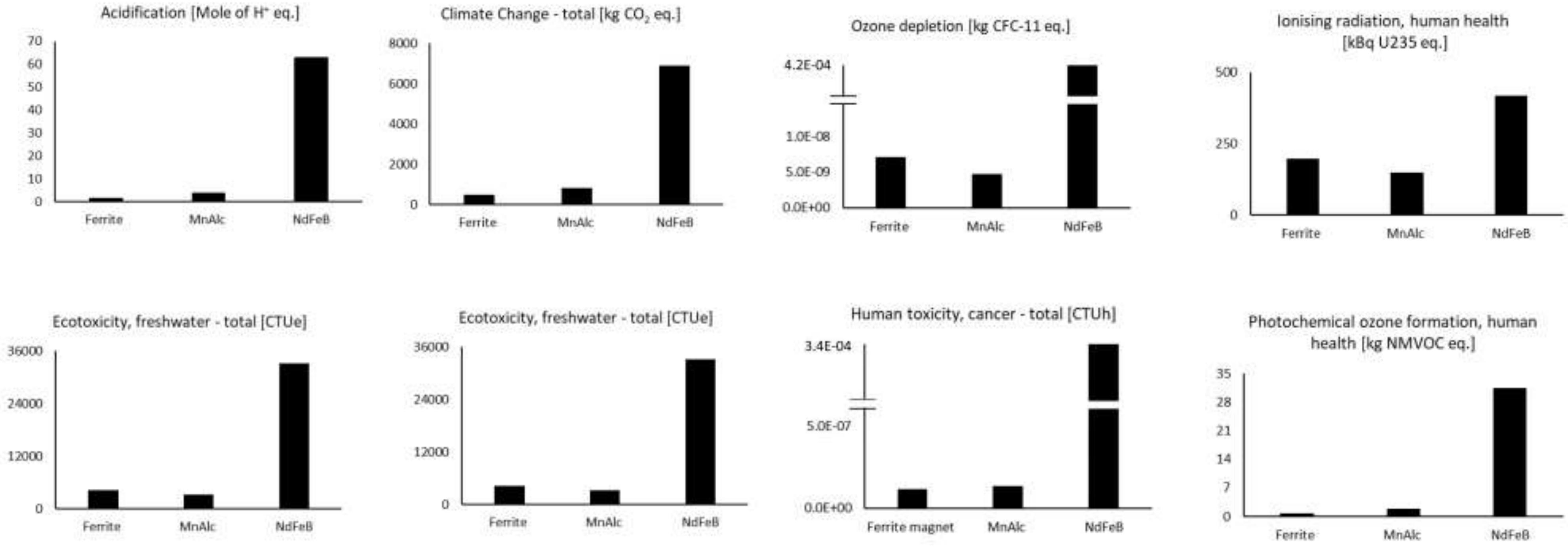
Assessment of environmental

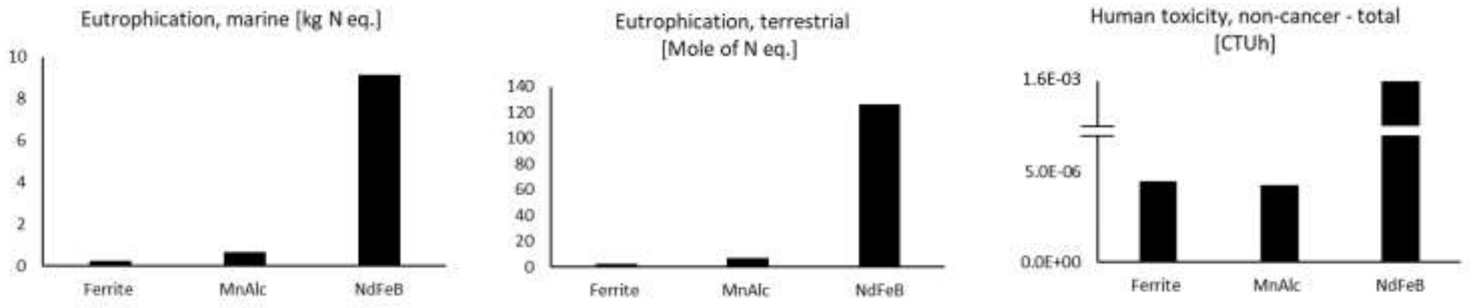




- The lowest impact of ferrite was estimated on the impact categories: climate change, particulate matter and resource use, fossils
- Impact saving around 35% of sintered ferrite magnets
- The environmental footprint confirms the raw material supply issues, mainly for MnAlC magnets
- The highest impact of ferrite manufacturing in the category of ionizing radiation is justified by the higher electricity consumption of ferrite production than MnAlC one
- The effect on ionizing radiation-human health is caused by the radionuclides produced by both the nuclear energy production, and the mineral oil gas extraction, used as energy carrier

Environmental impact assessment of manufacturing processes





comparison among sintered ferrite, MnAlC and NdFeB magnets

Environmental impact assessment of manufacturing processes

- The environmental burden of Nd-Fe-B far exceeds (also many orders of magnitude in the categories of eutrophication freshwater, ozone depletion and human health the other technologies in all the impact categories considered.
- The results show a possible emission saving of 93% and 87% by using sintered ferrite and Mn-Al-C, respectively, in the category of climate change.
- This advantage is explained by the avoided use of Nd and Dy which cause about 50% of the whole process emission of CO_2 eq. Their contribution on the process impact reach up to 98% in the category of eutrophication marine.

Thank you!

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