Supporting information

Life cycle assessment of rare earth elements-free permanent magnet alternatives: sintered ferrite and Mn-Al-C

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Table S1: Energy and mass balance of the two sintering routes (based on the production of 100 kg of final permanent magnet. *The quantity of dispersants, lower than 1% of the whole input, make them negligible for the analysis purpose).

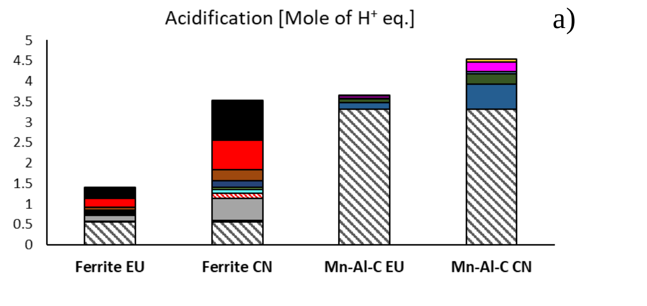
Process	Step	Input	Output
Ferrite thermal sintering	Mixing	0.5 kWh 13.3 kg $SrCO_3$ 89.0 kg Fe_2O_3 0.09 kg SiO_2 0.2 kg H_3BO_3	102.6 kg mixed powder
	Pelletizing	8.4 kWh	107 kg ball pellet (diameter 6 mm)
	Pre-sintering	195 kWh	96.2 kg $SrFe_{12}O_{19}$-SiO_2 2.4 kg Fe_2O_3 4.0 kg CO_2
	Dry crushing	44 kWh	Pre-sintered powder (<10 µm)
	Wet crushing	33 kWh 95.9 kg water 1.0 kg $CaCO_3$ 0.1 kg SiO_2 0.3 kg dispersants* 0.1 kg H_3BO_3	195.9 kg slurry
	Dehydration	18.5 kWh	133.3 kg slurry (75 wt.% solid) 62.6 kg water
	Moulding	55 kWh	1400 unit of compact magnet (Diameter 5 cm; heigh 1 cm; ρ: 3.8 g cm^{-3})
	Drying	96 kWh	1400 unit (=100 kg solid) 33.3 kg water
	Sintering	250 kWh	1400 units synthetized ferrite magnet
	Magnetization	350 kWh	1400 units ferrite PM (=100 kg) B_r 0.43 T; H_c 310 kA/m; $(BH)_{max}$ 35 kJ/m^3
Mn-Al-C sintering route	Mixing	0.5 kWh 72 kg Mn 29.5 kg Al 0.5 kg C	102 kg mixed powder (72 kg Mn, 29.50 kg Al; 0.5 kg C)
	Melting and casting	215 kWh	100 kg molten solution casting in cylinders (70 wt% Mn; 29.5 wt% Al; 0.5 wt% C) 2 kg Mn
	Homogenizing	94 kWh	100 kg ε-phase Mn-Al-C ($Mn_{53}Al_{45}C_2$)
	Quenching and Tempering	18 kWh	100 kg τ-phase Mn-Al-C (D: 4 cm; H: 3 cm; ρ: 5.1 g cm^{-3}) (Equivalent to 520 billets)
	Hot-extrusion	84 kWh	100 kg τ-phase Mn-Al-C (D: 1.5 cm; H: 22 cm)

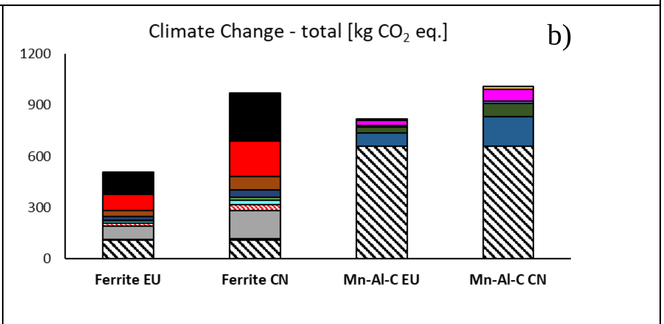
	Cutting	-	100 kg τ-phase Mn-Al-C (D: 1.5cm; 2 cm) Equivalent to 5720 units
	Compression work	19 kWh	100 kg τ-phase Mn-Al-C (D: 1.5; H: 1.6 cm) 5720 units Mn-Al-C magnet B_r 0.47 T; H_c 238.7 kA/m; $(BH)_{max}$ 35 kJ/m^3

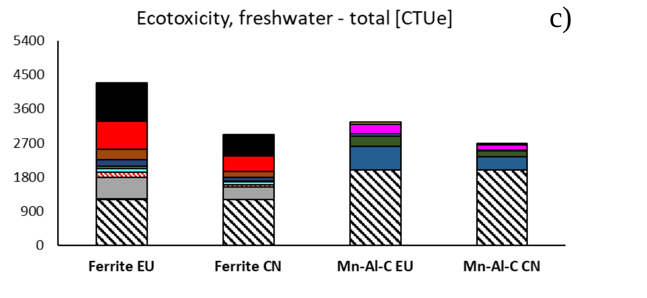
Table *S2*: Characteristics of machine selected for the processes.

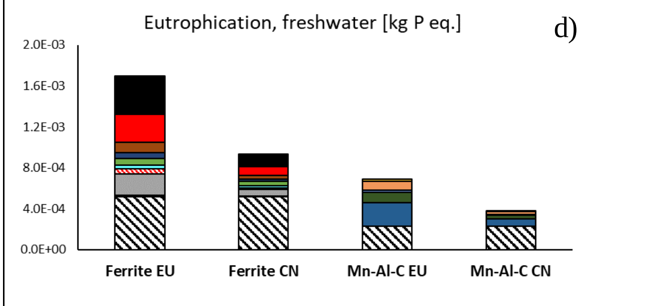
Process	**Step**	**Capacity**	**Reference**
Ferrite thermal sintering	Mixing	100L/batch	[1]
	Pelletizing	100 kg/h	[2]
	Pre-sintering	120 kg/h	[3]
	Dry crushing	200 kg/h	[4]
	Wet crushing	200 kg/h	[4]
	Dehydration	200 kg/h	[5]
	Moulding	100 kg/h	[6]
	Drying	270 kg/h	[7]
	Sintering	(2.5 kWh/kg)	[8]
	Magnetization	-	[8,9]
Mn-Al-C sintering route	Mixing	100L/batch	[1]
	Melting and casting	100 kg/h	[10]
	Homogenizing	400 L	[11]
	Quenching and Tempering	120 kg	[11]
	Hot-extrusion	-	[12]
	Cutting	-	
	Compression work	-	[13]

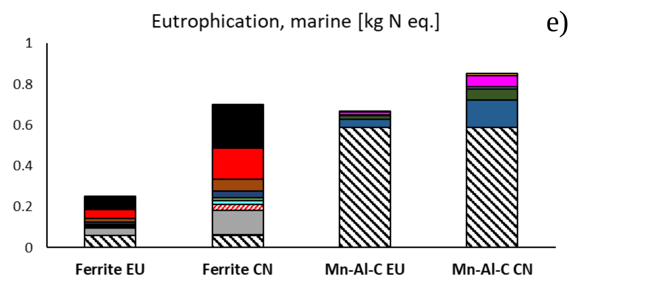
Environmental conservation

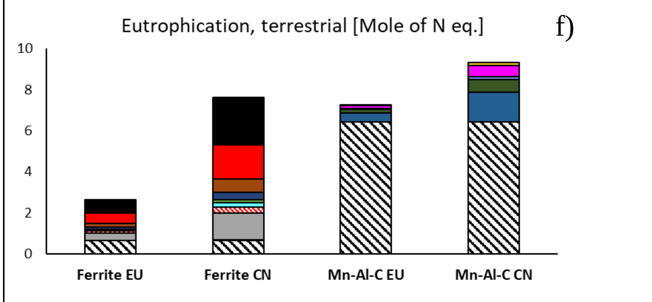


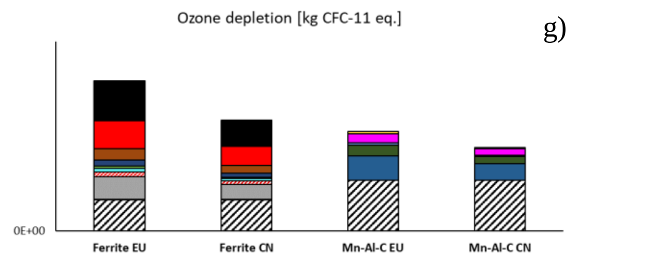




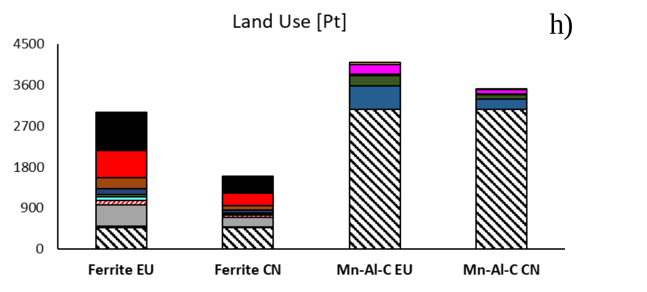


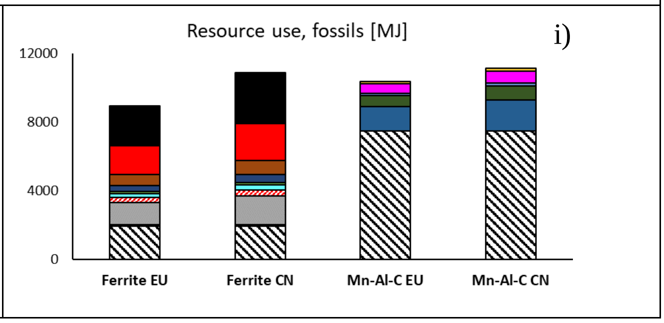






Resource depletion





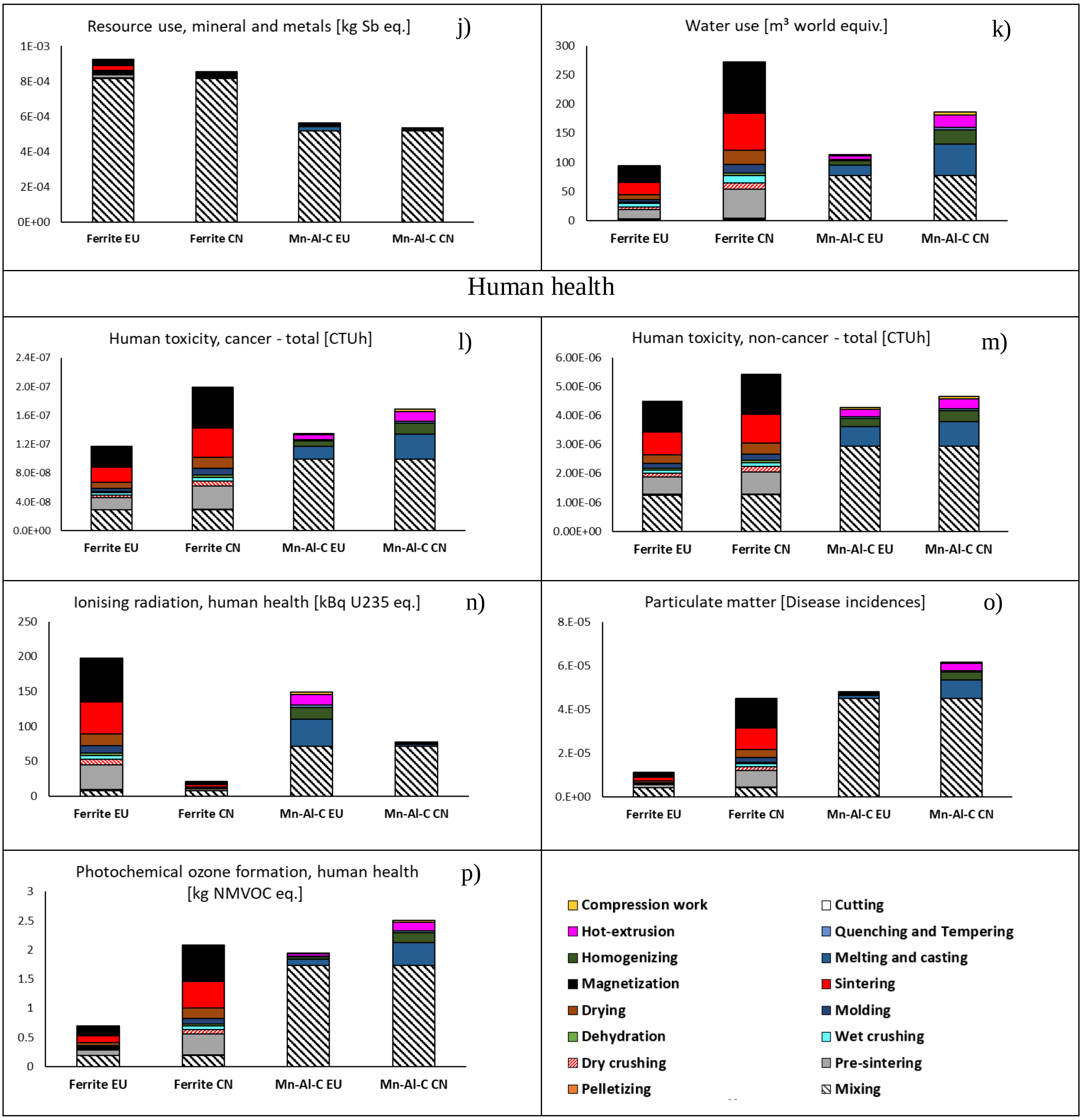
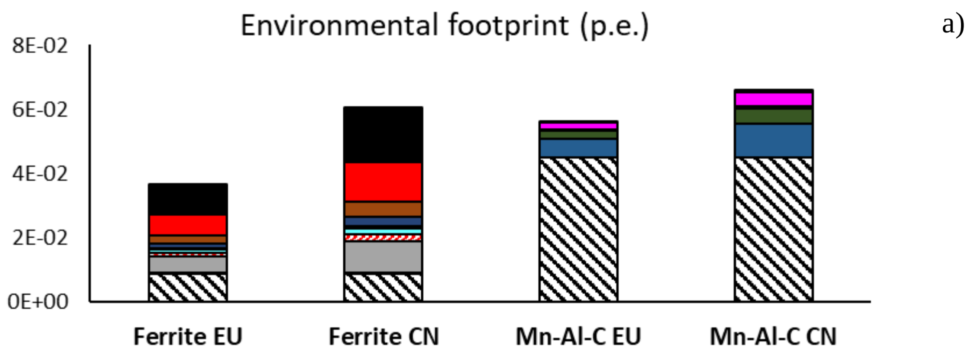


Figure S1 Assessment of environmental impacts in the categories of a) acidification, b) climate change, c) ecotoxicity, freshwater, d) eutrophication, freshwater, e) eutrophication marine, f) eutrophication terrestrial, g) ozone depletion, h) land use, i) resource use, fossils, j) resource use, mineral and metals, k) water use, l) human toxicity, cancer, m) human toxicity, non-cancer, n) ionizing radiation, human health, o) particulate matter, p) photochemical ozone formation, comparison between production processes of ferrite and Mn-Al-C magnets. Energy is supplied by Chinese grid mix (functional unit: 100 kg of magnets).



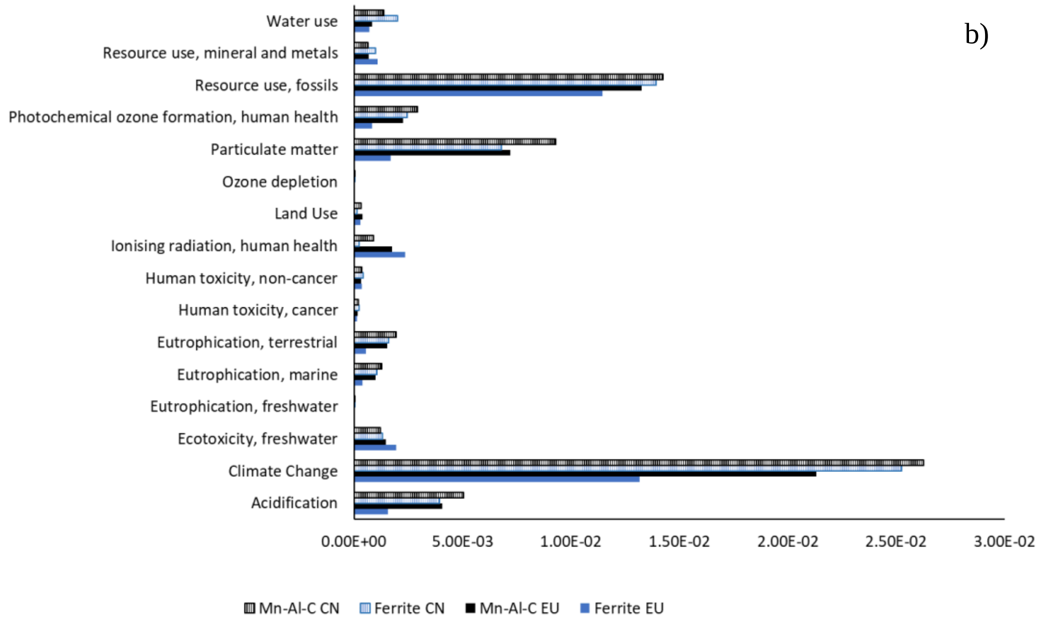
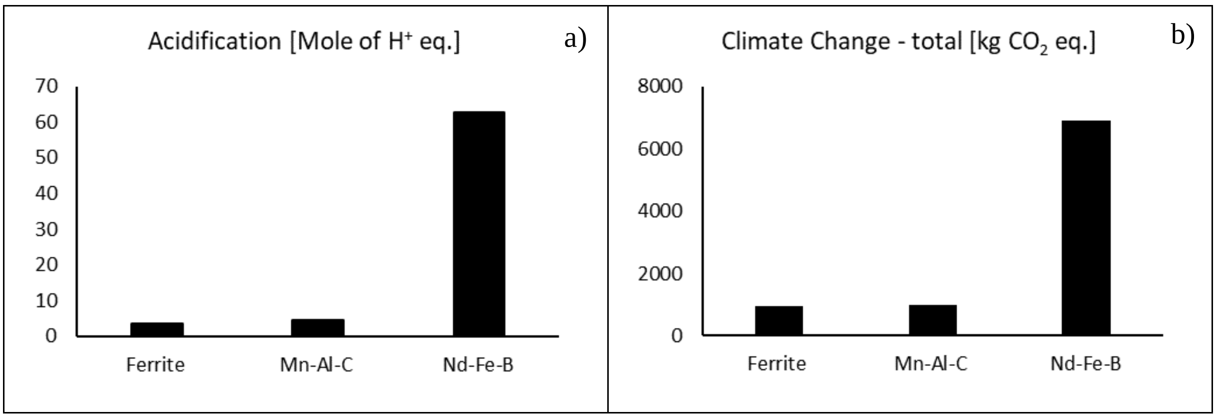
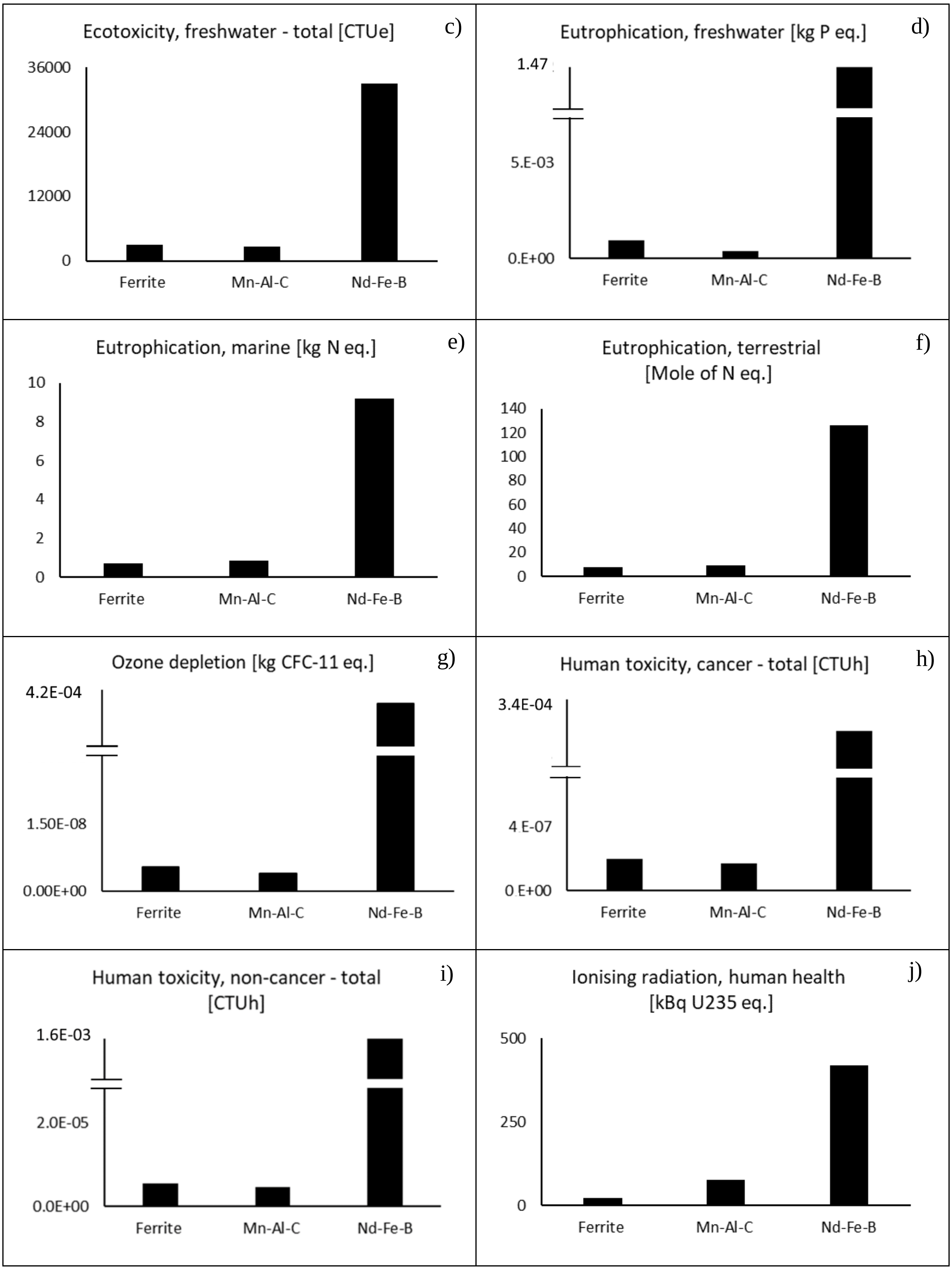


Figure S2: Assessment of environmental footprint: a) comparison between production processes of ferrite and Mn-Al-C magnets b) contribution of impact categories. Energy is supplied by Chinese grid mix (functional unit: 100 kg of magnets)




Ecotoxicity, freshwater - total [CTUe]
c)
36000
24000
12000
0
Ferrite
Mn-Al-C
Nd-Fe-B
Eutrophication, freshwater [kg P eq.]
d)
1.47
5.E-03
0.E+00
Ferrite
Mn-Al-C
Nd-Fe-B
Eutrophication, marine [kg N eq.]
e)
10
8
6
4
2
0
Ferrite
Mn-Al-C
Nd-Fe-B
Eutrophication, terrestrial [Mole of N eq.]
f)
140
120
100
80
60
40
20
0
Ferrite
Mn-Al-C
Nd-Fe-B
Ozone depletion [kg CFC-11 eq.]
g)
4.2E-04
1.50E-08
0.00E+00
Ferrite
Mn-Al-C
Nd-Fe-B
Human toxicity, cancer - total [CTUh]
h)
3.4E-04
4 E-07
0 E+00
Ferrite
Mn-Al-C
Nd-Fe-B
Human toxicity, non-cancer - total [CTUh]
i)
1.6E-03
2.0E-05
0.0E+00
Ferrite
Mn-Al-C
Nd-Fe-B
Ionising radiation, human health [kBq U235 eq.]
j)
500
250
0
Ferrite
Mn-Al-C
Nd-Fe-B

k)

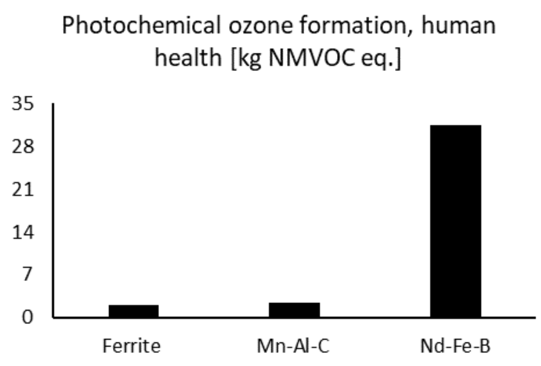


Figure S3: Environmental impact assessment of manufacturing processes in the categories of a) acidification, b) climate change, c) ecotoxicity, freshwater, d) eutrophication, freshwater, e) eutrophication marine, f) eutrophication terrestrial, g) ozone depletion, h) human toxicity, cancer, i) human toxicity, non-cancer, j) ionizing radiation, human health, k) photochemical ozone formation, comparison among sintered ferrite, Mn-Al-C and Nd-Fe-B magnets. Energy is supplied by Chinese grid mix.

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