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A sustainability assessment of the foundry production process in Italy

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ABSTRACT

Sustainability has become an essential goal for companies to preserve their competitiveness; the metal cast industry is facing several challenges due stringent environmental regulations, resulting in sustainability performance issues. The evaluation of the cast iron environmental footprint has become a key point to drive the sector towards a more sustainable future.

This study investigates the environmental performance of the cast iron manufactured by ten Italian foundries (named from A to J) by quantifying their product environmental footprint through the Life cycle assessment methodology. The scores of the surveyed foundries were compared with a benchmark value, that is representative of the average product manufactured by the Italian plants.

The product environmental footprint of the casts of seven out of the ten surveyed plants is lower than the benchmark one. Raw materials acquisition is the most impacting in all sites; its contribution to the total product environmental footprint ranges from 59 % (foundry J) to 94 % (foundry D). Raw materials acquisition is followed by melting. The raw materials contributing more to the cast iron environmental footprint are pig iron and ferroalloys, together with electricity. The three elements on average accounts for the 60 % of the score of the casts of the surveyed plants.

In all the considered plants climate change, particulate matter, resource, fossil fuels use and ecotoxicity are the most critical impact categories accounting for at least 70 % of the environmental footprint.

The reduction of the cast iron environmental footprint is challenging because it requires to intervene on a well consolidated production process without altering the product quality. However, the substitution of pig iron and ferroalloys with recycled inputs, although not easy to achieve could be effective to enhance the sector sustainability since it would reduce the scores associated with the climate change, resource use and ecotoxicity impact categories.

1. Introduction

In recent years sustainability has become an essential goal for companies to preserve their competitiveness. Industries are constantly under pressure to improve the environmental performance of their products and their manufacturing processes through the minimization of waste production and the prevention of pollutants emissions (Appolloni et al., 2022).

In 2020 in Europe (EU-27) industry was responsible for 22.16 % of the total greenhouse gasses emission, corresponding to 719,574 ktonne of CO_2-eq. In particular, the iron and steel industry was responsible for the emission of 69,832 ktonne of CO_2-eq i.e., the 9.7 % of the industrial GHGs emission (European Environment Agency, 2023). More specifically, in Italy in 2020, the manufacturing industry emitted 71,009 ktonne of CO_2, corresponding to the 32 % of the total of CO_2 emissions at national level, while the manufacturing of basic metals and fabricated metal products accounted for 17 % of the of CO_2 emissions of the industrial sector (Istat, 2022).

In terms of production, the European foundry industry is the third in the world for ferrous metals and the second for non-ferrous metals (Joint Research Centre Directorate B – Growth and Innovation Circular Economy and Industrial Leadership Unit and European IPCC Bureau, 2022). The annual production of castings in the EU-25 is estimated at 11.7 million tonne for ferrous metals and 2.8 million for non-ferrous metals. The Italian foundry industry is the second largest in Europe and the ninth largest in the world according with the level of production. With

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Germany, the Italian foundry industry produces nearly the 70 % of the European castings total volume. In 2023, 1038 foundries (ferrous and non-ferrous) were operating in Italy, employing roughly 24,000 people (AssoFond, 2023).

Italian foundries deal mainly with non-ferrous metals (866), while only a minor part of them (172) produces ferrous metals (19 % steel and 81 % cast iron). However, ferrous foundries have a higher revenue than the non-ferrous ones (10.8 million € versus 4.9 million €). The vast majority (80 %) of the Italian foundries is located in the Northern part of the country (AssoFond, 2023).

The metal cast industry is facing several challenges due to increasing global competition, stringent environmental regulations, emissions, and wastage, resulting in sustainability performance issues (Madan and Singh, 2023). Due to the growing concerns related with environmental sustainability, the evaluation of the cast environmental footprint through robust methodologies has become a key point to drive the sector towards a more sustainable future.

In Italy the foundry sector pays huge attention to the topics related with sustainability. Assofond, the sector's employers' association representing Italian foundry firms, is aware of the environmental impact associated with the foundry process and has actively worked on proposing schemes to quantify the environmental performance of Italian products with the aim of promoting the most sustainable ones. In 2022 the association supported the creation of the Product Category Rules (PCR) for cast iron, which were recently approved by the Italian Ministry for the Environment (Baldereschi et al., 2022) while the PCR for steel casting were already approved in 2021 and Assofond has scheduled a new PCR for non-ferrous metals, expected in 2024. The cast iron PCR describe the procedures that should be applied to measure the product environmental footprint (PEF) of cast iron manufactured in Italy and defines a representative product (the benchmark) against which the environmental performance of the casts should be compared. The PCR are complaint with the Recommendation 2021/2279 of the European Commission, which contains the guidelines on the use of the Environmental Footprint methods to measure and communicate the life cycle environmental performance of products and organizations (European Commission, 2021). The Commission Recommendation selected the Life Cycle Assessment (LCA) as the suggested methodology to measure the PEF.

LCA is in fact a comprehensive tool, codified in international standards (International Organization for Standardization, 2006, 2018) to help decision-makers identifying the solutions that best support sustainable development through the quantification of the environmental impact a product generates during its entire life (Hauschild et al., 2018). The strengthens of LCA lies in the fact that, by evaluating the environmental impact over multiple impact categories that can range from climate change to human toxicity, it takes into account all the effects associated to the manufacturing of a product. In addition, in LCA, environmental flows are quantitatively related to impact categories according to environmental mechanisms, resulting in characterization factors for each environmental flow (Valdivia et al., 2013). Moreover, the basic idea of LCA is that all environmental burdens connected with a product or service have to be assessed, back to the raw materials and down to waste removal thus avoiding positive ratings for measurements which only consist in the shifting of burdens (Klöpffer, 1997).

Various studies have performed LCAs on the cast iron manufacturing process; however, they showed some limitations as described in Section 2. For example, only a couple of them retrieved data directly from the plants and a comprehensive comparison among the environmental footprint of various plants has never been conducted.

Thus, this study collected data on the production process of ten Italian cast iron foundries with different capacities, melting technologies and binder systems with the aim of:

(1) Evaluate the environmental impact of the cast iron production process of the ten considered plants by estimating the environmental footprint and compare it against the benchmark defined in the PCR for cast iron (Baldereschi et al., 2022);
(2) Identify the impact categories over which the foundries show the best and worst environmental performance;
(3) Identify the most impacting phases of the cast iron manufacturing process;
(4) Identify the raw materials employed in the foundry sector that have the highest environmental impact.

2. Literature review

The sustainability of cast iron production has been the topic of various studies. For example, the environmental performance of the whole cast iron production process has been investigated in Mitterpach et al. (2017b), who analyzed the environmental impact associated to the manufacturing of grey cast iron to provide a basis to assist the foundry in lowering its environmental score. The same group of authors estimated the environmental impact related to the different phases of the cast iron manufacturing process to provide an assessment of the creation and use of waste foundry sand, finding that recycling waste foundry sand in the construction sector would result in significant savings in the consumption of resources (Mitterpach et al., 2017a). Moreover, Yilmaz et al. (2015) evaluated the impact of eleven Best Available Technologies (BATs) employed in cast iron production in various steps of the foundry process using as input parameters the average data for the European iron casting industry taken from literature.

A comparison among the carbon footprint of various melting technologies in the context of Germany was carried on in Finkewirth et al. (2022), who concluded that the rotatory drum furnace with an oxygen burner is associated to the lowest GHGs emissions; however, the study found that the result is highly dependent on the composition of the country's electricity mix. A recent study has evaluated the carbon footprint of various cast iron alloys, again in the German context, finding that the chemical composition of the alloy highly influences its environmental performance, with alloys containing higher percentage of scrap showing a lower footprint (Abdelshafy et al., 2022).

Other studies investigated the environmental impact of the manufacturing of different metals. Already in 2007 a study found that the global warming potential associated to the production of metals like titanium and aluminum is about ten times higher than the ones of steel and copper (Norgate et al., 2007). The comparison between the environmental performance of steel and cast iron has been evaluated in Joshi et al. (2011), who underlined the higher impact on human health of the steel production with respect to the cast iron one, and Olmez et al. (2016), who evidenced that steel production is associated with higher impacts on global warming with respect to cast iron. Yang et al. (2023) evaluated the carbon footprint of electric arc furnace steelmaking process under various smelting modes in the context of China.

A major issue of the considered works is the use of literature data to model the cast iron production process as done in three studies (Joshi et al., 2011; Norgate et al., 2007; Yilmaz et al., 2015). Only two studies (Mitterpach et al., 2017a, 2017b) performed a LCA with data directly collected at the plant's site. Both studies collected data for the cast iron plant of Hronec (Slovakia). In addition, only one study compared the performance of the different melting technologies applied in the foundry industry and evaluated solely the carbon footprint (Finkewirth et al., 2022). None of the cited studies investigated the environmental impact of the different binder systems.

However, a comparison among the environmental footprint of cast iron produced at various plants that exploit different melting technologies and binder systems is worth to clearly identify the more sustainable production methods and the most impacting phases of the manufacturing process.

In addition, the analysis presented in this study is not limited to the carbon footprint, but it includes sixteen impact categories, ranging from resources consumption, human health and ecosystems quality. This analysis allows to understand on which impact categories the cast iron production impacts more, thus identifying the environmental aspects on which the foundry sector should work to increase its sustainability.

Moreover, a comparison of the environmental impact of the cast iron manufactured at each of the considered plants versus the one of a product representative of the national average has never been performed, but is interesting to provide stakeholders with indications on best practices already adopted in the sector to enhance its sustainability.

3. Methods

3.1. Description of the foundry process

The ten surveyed plants are all located in Northern Italy, an area characterized by a high density of cast iron plants, where previous research on the environmental footprint of foundries has never been systematically performed. Moreover, the ten plants produce around 35 % of the national cast iron in terms of weight.

Cast iron is an iron-carbon alloy with a typical carbon content between 2.4 and 4 %; other metals such as manganese, molybdenum, sulphur, silicon and nickel could be present (Lazzarin and Noro, 2015). The basic cast iron foundry process foresees the following activities:

(1) Raw materials acquisition;
(2) Metal melting;
(3) Cores and mould preparation and casting of the molten metal into the moulds;
(4) Cooling and removing of the casts from the moulds;
(5) Finishing of the raw casting;
(6) Other processes typical of the considered plant (as for example, thermal treatment of the casts, transport of the casts to other sites for specific phases, as for example finishing, if it happens in a site different from the main one, testing of the casts, water, heating and energy used by the offices, water and energy for workers locker rooms).

Cast iron derives from the melting of pig iron together with various other materials (such as steel, ferroalloys and metals) in a furnace. Furnaces can be of three types: electric, rotary or cupola. The induction furnace is an electric furnace that has high flexibility in managing the different types of alloys and is currently the most used furnace in the foundry system; it normally produces one or two castings per day, because it requires a certain time for loading (for large castings of 100 t even 48 h). This system allows the creation of casts of all possible shapes and with a great variety of weights (from a few kg to 120 t). The rotary oven uses natural gas, sometimes mixed with oxygen. It is similar to the electric furnace in terms of casting and loading times, but it is a much more robust and can use elements containing high quantities of impurities. The rotary furnace also allows the production of casts of various shapes, but the cast's weights are lower with respect of those manufactured with an electric furnace. Finally, the cupola is similar to a small blast furnace: it uses petroleum or coke and works 24 h a day for at least 5 or 6 days a week. The cupola furnace usually shows a high efficiency since the input material loading is continuous. Generally, the cupola furnace allows the production of a high number of casts having the same shape (as for example in the automotive sector). On average, the weight of the casts is lower than 500 kg.

3.2. Life cycle assessment goal and scope definition

The aim of this study is the evaluation of the PEF of cast iron manufactured at the ten surveyed plants in compliance with the PCR for cast iron. Moreover, the PEF of the considered products is also compared with the one of a representative product (the benchmark), defined in the PCR for cast iron production. The benchmark product is defined in the PCR for cast iron approved by the Italian Ministry for the Environment in the framework of the "Made Green in Italy" initiative. The product, which is representative of the Italian average cast, has been built based on a screening study of the average values of the input materials of the furnace charge and the energy (thermal and electric) used at national level. Additionally, this study aims at identifying the impact categories over which the foundries show the best and worst environmental performance, such that stakeholders could assess which environmental aspects are more affected by cast iron manufacturing. Moreover, the most impacting phases and raw materials of the cast iron production process are identified to inform stakeholders on the areas where improvements in the manufacturing process could significantly reduce the environmental impact of foundries.

The functional unit (FU) of the study is 1 net tonne of cast iron at the gate of the foundry, thus a cradle to gate approach is followed. The system boundaries include the raw materials used as inputs for the casting phase (pig iron, iron scrap, ferroalloys, etc.), the five phases of the cast iron production process (melting, moulding, cooling, finishing and other processes typical of each specific plant), the water, thermal and energy consumption of the casting process and of the plant, the atmospheric emissions, wastewater and waste generated from the process and optional transports that can happen if one of the five phases takes place in a site different form the main one. Packaging and infrastructure have been excluded from the study, as well as transports to the clients, use phase of the cast and final disposal.

Background data from the Ecoinvent database have been used to model the input materials of the casting process, while the amount of each of the material that enters the production process has been measured at the plants sites. Water, thermal and energy consumption of the process, air emissions, wastes and optional transports data have been collected at the plants' sites. Furthermore, the gross and net production were retrieved from plants measurements. The system boundaries are represented in Fig. 1.

The SimaPro software v.9 has been used to compute the PEF; the Environmental Footprint (EF) v.3 method (Sala et al., 2018) has been selected to perform the LCIA (Life Cycle Impact Assessment) in compliance with the Commission Recommendation (EU) 2021/2279 (European Commission, 2021).

In addition to the characterization, normalization and weighting of the results have been performed to compare the environmental impact of the cast iron manufactured at the ten interviewed foundries with the benchmark described in the PCR. The normalization and weighting factors of the Environmental Footprint v.3 method are presented in (Sala et al., 2018) and reported in Table S3.1.

3.3. Life Cycle Inventory of the products manufactured at the ten considered plants

Ten Italian cast iron plants were surveyed between September 2022 and April 2023 and provided data on the type and quantity of raw materials used, on electric, thermal and water consumption, on the direct emissions measured at the plant's site and on the quantity and type of wastes generated in a reference year. The main features (reference year, gross production in the reference year and conversion factor from gross to net production) of the ten plants are summarized in Table 1.

Data for foundries from A to E were collected at the end of 2022, thus the plants selected 2021 as a reference year, whereas foundries from F to J were interviewed in 2023, and consequently chose 2022 as a reference year. Cast iron production in Italy in 2021 returned to the over one-million-ton threshold disastrously affected by the collapse in 2020 (CAEF, 2021); the five plants that selected 2021 as reference year confirmed their data for 2021 were not affected by the impact of the 2020 health crisis.

The ten plants have different production capacities, ranging from the 9899 t/year of gross production of foundry C to the 119,092 t/year of gross production of foundry F. The conversion factor reported in Table 1

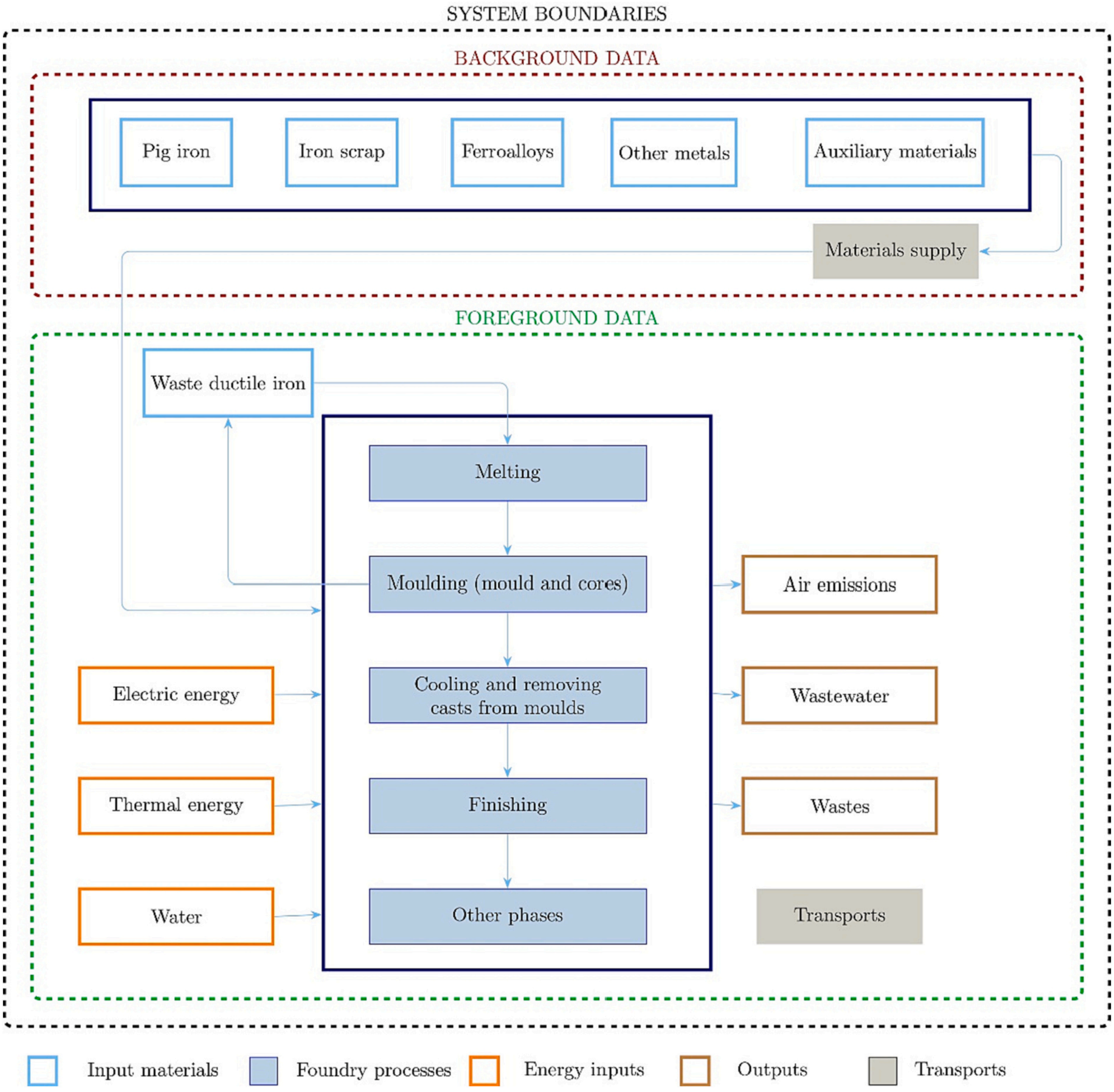

Fig. 1. System boundaries for the cast iron production process (adapted from Baldereschi et al., 2022).

Table 1
Reference year for data collection, gross production and conversion factors from gross to net production in the reference year of the ten cast iron plants considered in the study.

	A	B	C	D	E	F	G	H	I	J
Reference year	2021	2021	2021	2021	2021	2022	2022	2022	2022	2022
Gross production (tonne)	21,023	52,466	9899	18,122	17,361	119,091	36,675	12,846	26,599	52,771
Conversion factor from gross to net production (–)	0.63	0.60	0.33	0.79	0.79	0.66	0.68	0.66	0.60	0.67

multiplied by the gross production allows the determination of the plant's net production. The differences among the conversion factors are due to the different efficiency of the furnace energy mix, the type of cast iron manufactured by the foundry (normally spheroidal cast iron requires the use of magnesium in the production process, thus reducing the efficiency) and the casting dimension (larger castings shows lower conversion factors because of the longer time needed to charge the furnace and the consequent need of adjusting the casting composition several times). The melting and moulding technologies adopted by the plants are reported in Table 2.

The yearly electrical, thermal and water consumption and the average product recipe of the ten plants in the reference year are reported in Table 3.

The direct emissions of pollutants were also retrieved (Table 4). All the surveyed plants monitored dusts, while nitrogen oxides (NO_x) were measured in eight plants (A, B, D, F, G, H, I and J), sulphur oxides (SO_x) in three plants (F, I and J), Volatile Organic Compounds (VOC) in all plants excepts for foundry H and carbon monoxide (CO) in seven plants (A, B, D, F, G, H and I). Some plants monitored also other pollutants, such as polycyclic aromatic hydrocarbons (PAH), phenols, etc. The

Table 2
Melting and moulding technologies employed by the ten cast iron foundries included in the study.

Foundry	Cast iron type	% of production from			% of moulding	
		Electric furnace	Rotary furnace	Cupola furnace	Green sand	Resin sand
A	Lamellar and spheroidal	100	0	0	59	41
B	Spheroidal	100	0	0	100	0
C	Spheroidal	100	0	0	100	0
D	Spheroidal	68	32	0	0	100
E	Spheroidal	100	0	0	10	90
F	Lamellar	0	0	100	100	0
G	Lamellar	100	0	0	100	0
H	Lamellar and spheroidal	50	50	0	100	0
I	Lamellar and spheroidal	100	0	0	100	0
J	Lamellar	0	0	100	100	0

values are reported in Table S1.1.

Finally, the waste generated during the manufacturing process are listed in Table 4, together with the disposal method (recovery or landfill). The cast iron production process generates mainly blast and dust furnace slag, together with refractory materials and exhausted sand. All the surveyed plants with the exception of foundry D recover the blast furnace slag through various non specified processes that are out of the plant's control, while the major part of plants landfilled the dust furnace slag. Exhausted foundry sands are instead recovered in the building sector or as road foundations.

The background data were retrieved from the Ecoinvent v.3.7.1 database (Wernet et al., 2016). The modelling of the Italian electricity mix is described in Supplement S2.

3.4. Benchmark product

Data for the modelling of the benchmark was provided by Assofond. The benchmark was constructed considering an average recipe based upon the process inputs with two kinds of weights: the type of furnace and the binder used. The furnaces are of three types: 1) the cupola, getting energy from coke; 2) the electric furnace and 3) the rotary furnace, that gets energy from natural gas. The binder systems are green bounded sand and in sand-resin. The production process is, therefore, the result of a weighted average of the various casting and binder systems used to produce the raw iron castings. The benchmark was therefore constructed according to the production techniques indicated in Table 5.

Table 3
Average product recipe and energy, thermal and water consumption at the ten considered companies. Values are expressed per gross ton of cast iron. The ferroalloys considered are FeSi (Ferro silicon), SiC (Silicon Carbide), FeSiMg (Ferro silicon magnesium), FeMn (Ferro manganese), FeCr (Ferro chromium), NiMg (Nickel Magnesium), FeMoSi (Ferro silicon molybdenum), FeMo (Ferro molybdenum), while the metals are Cu (Copper), Sn (Tin), Ni (Nickel), Sb (Antimony), Mo (Molybdenum).

	Unit	A	B	C	D	E	F	G	H	I	J
Pig iron	tonne	0.253	0.195	0.327	0.484	0.443	0.146	0.159	0.491	0.090	0.155
Iron scrap	tonne	0.328	0.404	0.044	0.369	0.304	0.338	0	0.246	0.490	0.469
Waste ductile cast iron	tonne	0.419	0.350	0.550	0.080	0.267	0.507	0.636	0.245	0.437	0.376
Waste ductile iron	tonne	0	0	0	0	0	0	0.247	0	0	0
Ferroalloys	tonne	2.7×10^2	2.4×10^2	1.3×10^2	1.4×10^2	1.9×10^2	2.8×10^2	1.0×10^2	1.3×10^2	1.2×10^2	3.4×10^2
Metals	tonne	1.7×10^3	1.8×10^3	4.9×10^2	4.5×10^3	1.8×10^3	2.9×10^4	1.8×10^3	9.6×10^4	8.5×10^4	1.1×10^3
Refueling	tonne	1.5×10^2	3.2×10^4	1.4×10^3	1.9×10^2	1.5×10^2	0	2.7×10^2	1.1×10^3	1.8×10^3	0
Inoculant	tonne	0	4.4×10^3	1.6×10^3	6.9×10^3	3.7×10^3	5.7×10^4	1.6×10^3	2.2×10^4	2.3×10^4	3.7×10^3
Scorifying	tonne	1.7×10^3	5.5×10^4	9.7×10^4	4.1×10^3	1.9×10^3	3.1×10^2	3.3×10^4	7.1×10^4	1.3×10^3	5.5×10^2
Spheroidizer	tonne	0	0	1.4×10^2	1.4×10^2	9.9×10^3	0	0	0	0	0
Graphite	tonne	0	2.1×10^2	0	0	0	2.8×10^3	2.7×10^4	1.6×10^3	2.4×10^2	0
Refractory	tonne	2.1×10^3	5.4×10^3	6.6×10^3	4.3×10^3	5.8×10^3	2.2×10^3	2.2×10^3	0	4.2×10^3	0
Electricity (Italian grid)	MJ	5344	4218	5050	2627	4087	1160	3734	2891	4539	1347
Electricity (solar)	MJ	0	0	0	0	133	0	0	84	0	0
Natural gas	MJ	1234	523	793	2534	154	367	356	1174	430	671
Coke	MJ	0	0	0	214	0	3006	0	43	0	3982
Water	m^3	1.43	1.26	1.64	0.70	0.32	0.93	1.36	1.46	0.00	1.37

Table 4
Emissions released in the atmosphere and waste generated by the ten considered plants. Values are expressed in kg per gross tonne of cast iron. NO_x: nitrogen oxides, SO_x: sulphur oxides, VOC: volatile organic compounds; CO: carbon monoxide. NM: not monitored.

	A	B	C	D	E	F	G	H	I	J
Dust	0.108	0.044	0.027	0.062	0.080	0.059	0.074	0.067	0.066	0.088
NO_x	0.042	0.029	NM	0.014	NM	0.181	0.090	0.392	0.164	0.560
SO_x	NM	NM	NM	NM	NM	0.045	NM	NM	0.134	0.551
VOC	0.289	0.334	0.008	0.031	1.704	0.072	0.289	NM	0.618	0.520
CO	0.039	0.250	NM	0.157	NM	0.065	2.199	0.006	0.231	NM
Blast furnace slag - recovery	32	37	30	0	65	49	48	287	48	145
Blast furnace slag - landfill	0	0	8	73	0	13	0	0	3	0
Dust furnace slag - recovery	0	0	0	0	0	0	0	2	5	0
Dust furnace slag - landfill	1	3	0	1	1	13	0	0	0	11
Sand - recovery	0	0	0	0	0	0	0	1	0	0
Refractory - recovery	6	7	0	10	0	0	0	10	3	0
Spent foundry sand - recovery	179	181	206	75	44	156	77	192	107	0
Spent foundry sand - landfill	0	0	31	0	0	0	53	0	0	0
Other dust - recovery	89	123	0	0	62	15	1	0	5	23
Other dust - landfill	0	0	0	0	0	0	0	0	0	21

Table 5
Melting and moulding techniques adopted to produce cast iron in Italy (% with respect to total cast iron production in Italy).

Moulding technique		Melting technique	
Binder	% Production	Furnace	% Production
Green	84 %	Cupola	60 %
		Electric	10 %
		Rotary	30 %
Sand resin	16 %	Electric	90 %
		Rotary	10 %

3.5. Comparison among the benchmark and the products of the surveyed foundries

The environmental performance of the casts manufactured by the interviewed plants was compared with the benchmark. The comparison with the benchmark was performed to inform the interviewed companies on the position of their product with respect to an average one.

A weighting approach has been applied to derive the PEF of the benchmark product and the impact of the different phases of the manufacturing process. In this context single-score indicators should be preferably used for decision-making since are more understandable by stakeholders and companies (Roesch et al., 2020). Moreover, the weighting approach has been chosen also because in 2018 in Italy a new label based on the PEF has been introduced by the decree 56/2018 in the framework of the initiative "Made Green in Italy" (Ministero dell'ambiente e della tutela del territorio e del mare, 2018). The labelling scheme, which is voluntary, applies the weighting factors of the EF v.3 method (Sala et al., 2018) and presented in Table S3.1 and classifies products into three classes, A, B and C. Class B represents the average product. The labelling scheme is based on the aggregation of the weighted scores of the three most relevant environmental impact categories according to the PCR (climate change, particulate matter and resources use – minerals and metals). The benchmark score is 163.92 mPt (Baldereschi et al., 2022). The classification scheme is reported in Table S4.1. The use of a weighting approach that applies the same weighting factors as the labelling scheme of the "Made Green in Italy" initiative allows the surveyed companies to understand which is the environmental performance of their product with respect to the benchmark and if they could join the "Made Green in Italy" initiative.

4. Results and discussion

4.1. Life cycle assessment – characterization

The results of the characterization of the benchmark and of the products manufactured at the ten surveyed plants are reported in Table 6. Foundry C exhibits the worst environmental performance on all the impact categories with the exception of "Human Toxicity – cancer". This outcome is due to the fact that in the reference year (2021) Foundry C produced mainly special casts that contained high quantities of molybdenum, nickel and ferroalloys; the extraction of those elements generates relevant impacts on the category "Resource use – minerals and metals", as witnessed by the fact that the characterized value on the mentioned impact category for Foundry C is ten times higher with respect to the benchmark and the other foundries.

Although the energy consumption of Foundry C during the production process (melting, moulding, cooling, finishing and other phases) is similar to that of other plants such as Foundry B and I, Foundry C's impact on climate change is 1.5 times higher than the benchmark. The reason of the high impact of Foundry C on climate change should again be attributed to the raw material acquisition phase since the mining and processing of ferroalloys, molybdenum and nickel cause high energy consumption thus justifying the impact of Foundry C on the "climate change" category.

The use of relevant quantities of ferroalloys and metals has been linked to high impacts on climate change also in Abdelshafy et al. (2022). The energy consumption in the material acquisition phase gives an explanation for the high score (1.6 times than the benchmark) of Foundry C on the category "Resource use- fossils" too. Foundry C shows also a score 6.5 times higher than the benchmark on the category "Ecotoxicity – freshwater" and a score 23 times higher than the benchmark on the category "Acidification". Metals mining is known to be a source of environmental pollution particularly on terrestrial acidification and ecotoxicity (Rachid et al., 2023).

Given all these aspects, even if foundry C has renovated its plant, is environmental performance is poor. After the results of the present study, the company discussed with its client the environmental issues related with the manufacturing of special casts and decided to reduce the amount special casts produced. Thus, in 2023 the environmental performance of foundry C should have been improved. A new assessment of Foundry C's PEF is scheduled for 2024.

Table 6
Results of the characterization of the production of 1 net tonne of cast iron at the ten surveyed plants and for the representative product (benchmark, Bck).

Impact category	Unit	Bck	A	B	C	D	E	F	G	H	I	J
Climate change	kg CO_2 eq	2322	1972	1671	3462	1740	2111	1155	2838	1869	1341	1241
Ozone depletion	kg CFC_{11} eq	1.9×10^{-4}	1.8×10^{-4}	1.5×10^{-4}	2.7×10^{-4}	1.4×10^{-4}	1.6×10^{-4}	1.8×10^{-4}	2.1×10^{-4}	1.4×10^{-4}	1.5×10^{-4}	2.2×10^{-4}
Ionizing radiation	kBq U_{235} eq	128	180	158	253	111	147	120	178	123	147	139
Photochemical ozone formation	kg NMVOC eq	9.2	7.8	6.9	30.1	8.3	9.2	5.1	12.5	9.0	5.9	6.2
Particulate matter	disease inc.	3.6×10^{-4}	2.8×10^{-4}	3.2×10^{-4}	4.9×10^{-4}	3.1×10^{-4}	3.3×10^{-4}	9.8×10^{-5}	2.3×10^{-4}	2.0×10^{-4}	1.8×10^{-4}	1.6×10^{-4}
Human toxicity, non-cancer	CTUh	1.1×10^{-4}	3.7×10^{-5}	3.9×10^{-5}	1.3×10^{-4}	5.2×10^{-5}	4.6×10^{-5}	3.8×10^{-5}	4.9×10^{-5}	3.7×10^{-5}	2.4×10^{-5}	7.5×10^{-5}
Human toxicity, cancer	CTUh	1.1×10^{-5}	6.2×10^{-6}	5.2×10^{-6}	1.3×10^{-5}	6.4×10^{-6}	7.9×10^{-6}	4.7×10^{-6}	1.1×10^{-5}	7.3×10^{-6}	3.4×10^{-6}	2.1×10^{-5}
Acidification	mol H+ eq	9.6	8.9	8.2	212.9	11.1	9.8	5.8	11.8	8.9	7.3	7.3
Eutrophication, freshwater	kg P eq	0.89	0.79	0.83	2.5	0.87	0.89	0.46	1.13	0.76	0.49	0.52
Eutrophication, marine	kg N eq	2.02	1.81	1.7	4.92	1.97	2.07	1.25	2.65	2.08	1.62	1.61
Eutrophication, terrestrial	mol N eq	20.9	18.7	17.6	59.1	20.9	21.2	13.3	27.4	21.6	16.5	17.1
Ecotoxicity, freshwater	CTUe	60,369	46,497	48,221	388,832	65,343	62,493	27,351	77,156	50,132	30,542	33,353
Land use	Pt	10,263	11,578	10,742	24,391	8937	12,010	6403	14,990	8875	9142	6821
Water use	m^3 depriv.	253	363	341	735	417	346	203	412	286	351	226
Resource use, fossils	MJ	27,571	26,991	25,127	43,641	22,383	27,020	20,153	34,728	24,103	19,865	22,664
Resource use, minerals and metals	kg Sb eq	4.2×10^{-2}	2.5×10^{-2}	2.3×10^{-2}	3.5×10^{-1}	5.1×10^{-2}	8.7×10^{-2}	2.2×10^{-3}	9.1×10^{-2}	2.4×10^{-2}	2.6×10^{-2}	1.1×10^{-2}

On the contrary, Foundry F shows the best performance on multiple categories. Its score on climate change is half of the benchmark, the score on photochemical ozone formation is 0.55 with respect to the benchmark, the one on particulate matter is 0.27, the one on acidification 0.6 and the one on "Resource use – minerals and metals" 0.12. Foundry F exhibits the best environmental scores also on the "Eutrophication – freshwater", "Eutrophication – marine", "Eutrophication-terrestrial", "Ecotoxicity – freshwater", "Land use" and "Water use" impact categories. Foundry F, which deals mainly with the automotive sector, has adopted a highly standardized production process, which has been optimized to reduce both the electricity and the thermal consumption. It is interesting to note that, although Foundry F and J employ cupola furnaces and thus utilize coke in the production process, their scores on climate change are the lowest among the surveyed plants. This can be attributed to the fact that Foundry F and Foundry J are the one with the highest capacity among those that were surveyed and use high quantities of iron scrap and waste ductile iron. All these factors contribute to the low scores of the plants on the climate change impact category given the fact that the CO_2-eq emissions are mainly linked with the use of pig iron and the energy consumption. The low scores of foundry F on "Acidification", eutrophication, ecotoxicity and "Resource use – minerals and metals" should be attributed to the fact that in the average product recipe molybdenum and antimony are not present.

The excellent performance of Foundry I on human toxicity (both cancer and non-cancer) and fossil fuel consumption (the indicators for which Foundry I has the lowest scores among the surveyed plants) is mainly due to a very low use of pig iron in the manufacturing process, which is substituted by iron scrap and waste ductile iron. Foundry J instead shows the worst performance on the category "Human toxicity – cancer" (a score 1.9 times higher than the benchmark) because of high atmospheric emissions of nitrogen and sulphur oxides during the melting phase.

4.2. *Life cycle assessment - weighting*

Even when considering the weighted results, foundry C clearly exhibits the worst environmental performance among the interviewed plants, while foundry F shows the best performance (Fig. 2). Foundry C impacts mainly on mineral and metals consumption, acidification and eutrophication. The reason is again the use of high quantities of ferroalloys (mainly NiMg and FeMoSi), the mining and processing of which are associated with high impacts on the three mentioned categories. The comparison with the benchmark evidence that the major part of products of the surveyed plants show a better environmental performance with respect to the average Italian cast. Six foundries fall in the best performing class (class A) according to the "Made Green in Italy" classification scheme (foundries A, B, F, H, I and J), one in class B (foundry D) and three (foundries C, E and G) in the worst performing class (class C). The detailed results are shown in Table S5.1. The impact categories over which the foundry process impacts more are climate change, particulate matter, resource use (minerals and metals), fossil fuels use and ecotoxicity – freshwater. In all the considered plants these five impact categories account for at least 70 % of the total impact (Fig. 3). On average, the five impact categories account for the 75 % of the total impact of the ten considered plants; the value ranges from the 70 % of Foundry J to the 80 % of Foundry E. Climate change on average accounts for the 19 % of the total impact, particulate matter for the 15 %, resource use (minerals and metals) for the 17 %, resource use (fossils) for the 14 % and ecotoxicity-freshwater for the 10 %. Foundry C again exhibits a slightly different pattern, with climate change and particulate matter impacting less than acidification. Foundry J instead has a significant impact on "Human toxicity – carcinogen". Climate change is the most relevant source of environmental impact for five companies (foundries A, F, H, I and J) and for the benchmark product, while "Resources consumption, minerals and metals" is the most impacting category for foundries C, D, E and G.

Foundry B instead impacts more on particulate matter. It is interesting to note that the foundries in which climate change is the most impacting category are the ones with the lowest single-scores, while the ones impacting more on "resource use - minerals and metals" are the ones with the highest single-scores. The use of high quantities of virgin metals, ferroalloys and pig iron is associated with worst environmental performances.

In all foundries the most impacting phase is represented by the raw material acquisition (Fig. 4). The raw material acquisition accounts on average for the 74 % of the foundry's total impact; the value ranges from the 58 % of Foundry J to the 94 % of Foundry C. This phase in fact includes the extraction, processing and transport of the raw materials used by the foundry in its manufacturing process. Thus, it is not surprising that in the case of Foundry C, which uses high quantities of ferroalloys to manufacture special cast iron, the impact of the materials acquisition accounts for barely the total impact of the production process.

The "raw material" phase is followed by melting, that on average accounts for the 15 % of the total impact of the foundry in the ten considered plants (values range from 3.4 % of Foundry C to 30 % of Foundry J) in which the consumption of energy is relevant, and by moulding, that accounts on average for the 7 % of the total impact of the foundry. The other phases (cooling, finishing and other processes)

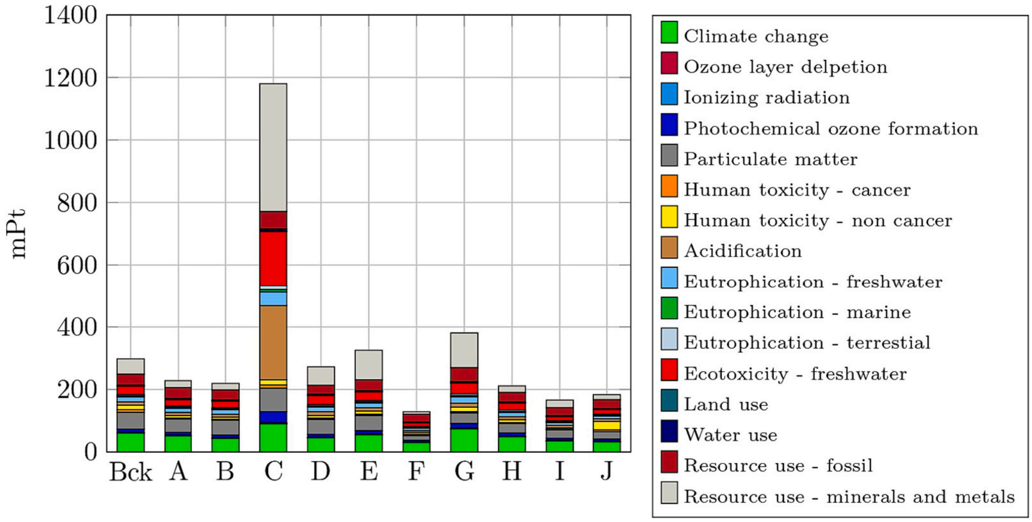

Fig. 2. Weighted results for the production of 1 net tonne of cast iron at the ten interviewed plants and for the representative product (benchmark, Bck).

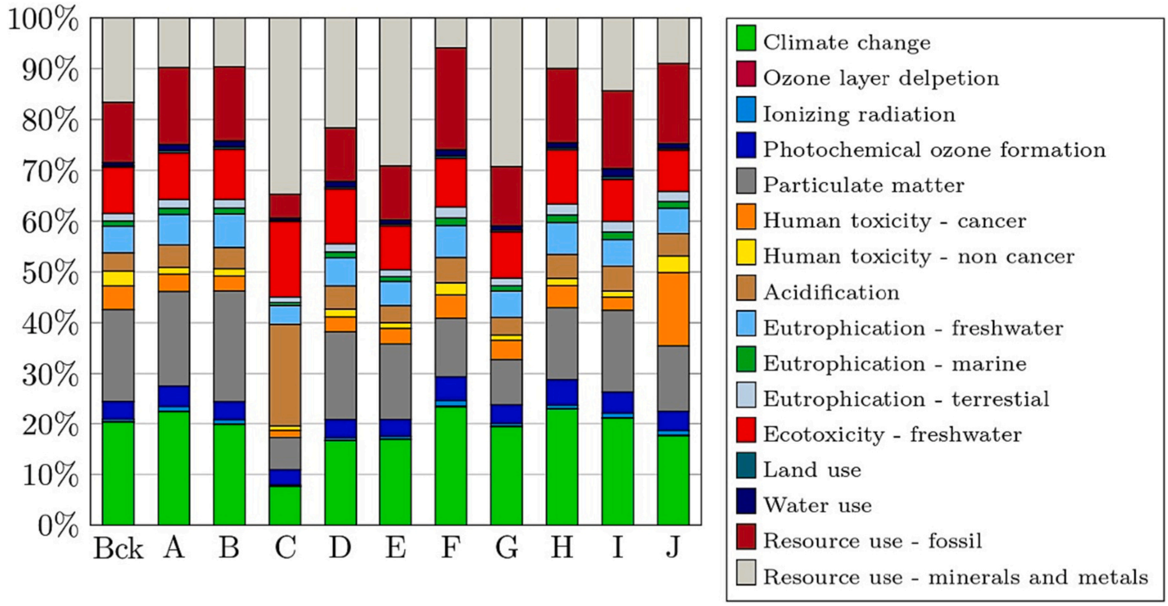

Fig. 3. Impact of the foundry process by impact category at the ten surveyed plants and for the benchmark product (Bck).

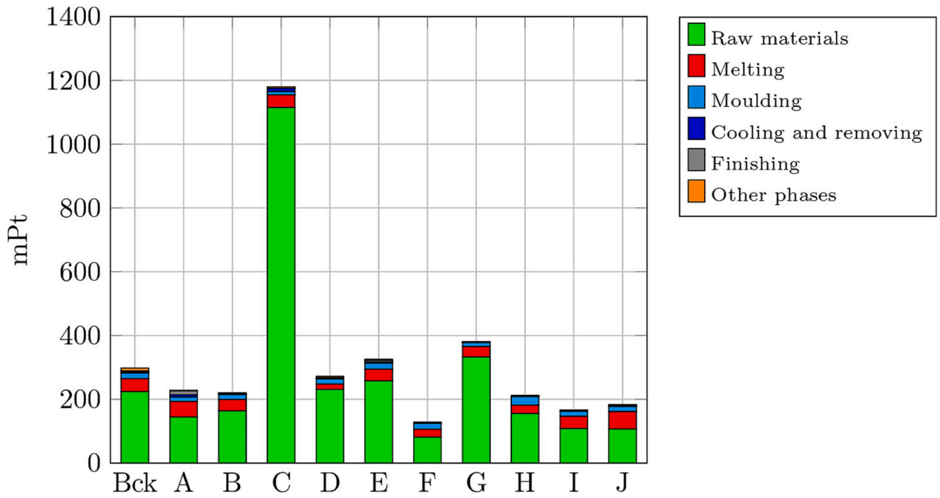

Fig. 4. Environmental footprint (Weighted results) for the production of 1 t of net cast iron at the surveyed plants disaggregated by activity and comparison with the average Italian product (benchmark, Bck).

contribute less to the total environmental impact of the foundries.

Pig iron is the input material of the foundry process that contributes most to the total impact in the major part of the interviewed plants, except for foundry C, where the majority of the impact is caused by ferroalloys and other metals. On average the pig iron accounts for the 30 % on the total impact of the foundry; the range goes from 11 % (Foundry C) to 52 % (Foundry H). Besides pig iron, other relevant sources of impact are: the electricity used for melting in the foundries employing electric furnaces, the ferroalloys and the metals such as nickel, antimony and molybdenum (Fig. 5). The impact of the electricity used for melting is clearly lower in foundry F, J, D and H, which are the plants working with cupola furnace (foundry F and J) or with both electric and rotary drum furnaces (foundries D and H). More specifically, the electricity used for melting is the second source of impact for Foundries A and I, while the ferroalloys are the second source of impact for Foundries B, D, E and G.

Other materials used in the melting phase represent the second source of impact for Foundries F, H and J. Again, in Foundry C the primary source of impact are "other metals" (accounting for 45 % of the plant's total impact), followed by the ferroalloys (32 %) and pig iron (11 %).

The same companies (F, J, D and H) show a higher impact on "melting – other materials" because of the fossil fuels used in the melting process (coke for foundry F and J and natural gas for foundries D and H). Foundry J shows also a high impact linked with the emission in the atmosphere of the melting phase. In fact, as reported in Table 5, the company has higher NO_x and SO_x emissions with emissions with respect to the other interviewed plants. Both the pollutants are renowned for their carcinogenic effects (Amadou et al., 2023; Tuśnio et al., 2020).

It should also be underlined that foundries employing sand-resin binder systems generally tend to show higher environmental impacts with respect to those producing green sand binder. In fact, foundries D, which produces only sand-resin castings, and E, which has a production process shifted mainly towards sand-resin casts, show lower environmental performances with respect to other foundries with a similar production level producing only green bounded sand casts. The inclusion of elements such as resin, binders and catalysts obviously raise the impact of the process and, additionally, sand-resin binders are

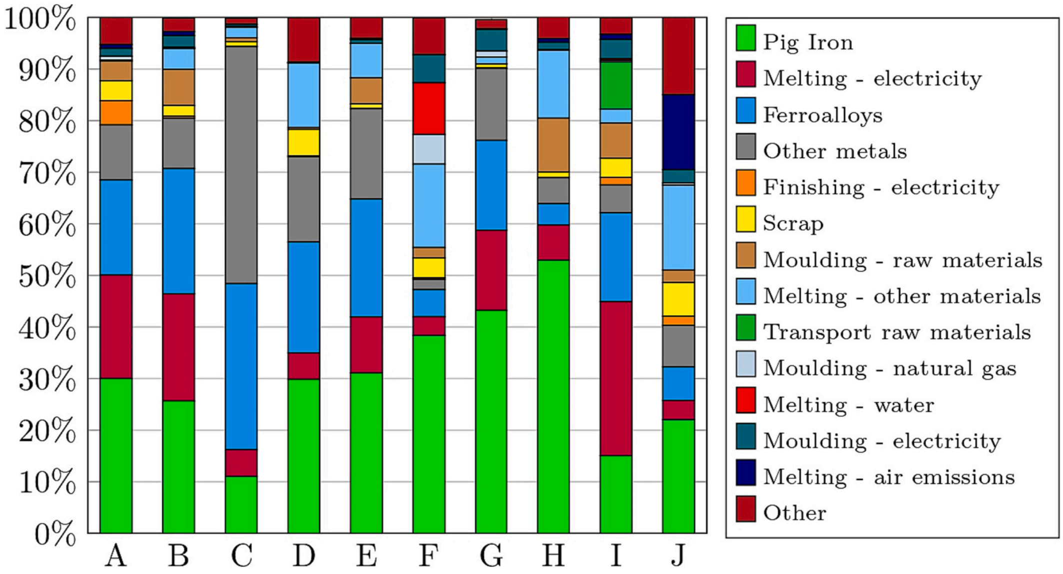

Fig. 5. Contribution of the inputs of the foundry process to the total impact expressed as percentage.

commonly used by foundries producing special casts, which show a higher environmental impact.

Overall, some considerations can be derived from the present analysis. At first, the environmental impact of the foundry process is strictly linked with the raw material acquisition phase, and specifically with the impact of pig iron production (Fig. 5). Foundries using lower quantities of pig iron show a lower total environmental impact. As an example, Foundries F, J and I, which employ the lowest quantities of pig iron among the interviewed companies, are those that also show the three lowest values of environmental impact. In this context it should be underlined that foundries F, J and I were interviewed in 2023 and provided data relative to the average product recipe of 2022, while foundries from A to E, interviewed between September and December 2022, provided data on raw materials utilized in 2021. It is reasonable to suppose that in 2022, because of the reduced availability and the increased cost of pig iron due to the geopolitical context (war between Ukraine and Russia, two of the main pig iron exporters as underlined by Guberman (2022)) those companies were forced to decrease the quota of pig iron in their production process, thus lowering their impact.

Secondly, as evidenced by Finkewirth et al. (2022), the environmental performance of the different melting technologies is related to the composition of the electricity mix of the country where the manufacturing process takes place. The use of electricity mixes with high shares of fossil fuels, such as the Italian one, increases the environmental impact on the "Climate change" category of the foundries equipped with electric furnaces; thus, foundries employing cupola furnaces show lower greenhouse gasses emissions with respect to the ones having electric furnaces.

Thirdly, companies producing high quantities of cast iron tendentially show lower scores with respect to those producing less. In fact, foundries F, J and B, which are the ones producing the highest quantities of casts, perform better with respect to the benchmark. The reason is linked with the high efficiency and optimization of the production process, which is designed to minimize costs and consequently fossil fuel consumption.

Finally, companies (such as Foundry C) producing special casts that require significant quantities of ferroalloys or metals such as Nichel and Antimony, exhibit the highest environmental impact.

4.3. Comparison with literature

The numeric results obtained in this study (both the characterized and the weighted results) are hardly comparable with the ones of other studies. For example, a comparison of the characterized values proposed by Yilmaz et al. (2015) is difficult since the authors used the ReCiPe 1.07 LCIA method for the global warming potential, freshwater and marine eutrophication and photochemical ozone creation potential categories, the USEtox for human and ecotoxicity, the CML 2001 for acidification, abiotic depletion and finally the EDIP 2003 for ozone depletion, all at mid-point level.

Moreover, the functional unit employed by Yilmaz et al. (2015) is 1 metric tonne of metal charge to the blast furnace, while the functional unit of the present study is 1 net tonne of cast iron at the gate of the foundry. Additionally, the cast iron production process phases considered in Yilmaz et al. (2015) slightly differs from the ones of this study: Yilmaz et al. (2015) considered only the raw material transportation instead of the raw material acquisition that includes raw material production; excluded the electricity from the melting and moulding process to have a separate phase called "electricity" which considers all the electrical consumption of the cast iron production process and selected the landfill as the base option for waste disposal.

Furthermore, the aim of the study of Yilmaz et al. (2015) was to identify and compare the environmental benefits and impacts of the best available technologies applicable to the iron casting process. However, some general considerations can still be drawn.

For example, the contribution of the melting phase is relevant over the categories "Global warming potential", "Acidification", "Photochemical ozone creation potential" and "Abiotic depletion – elements and fossils". The result is in agreement with the findings of the present study; in fact, the melting phase is the second most impacting phase, after the raw material acquisition and the categories over which it contributes more to the final score are "Climate change" and "Resource use – fossil".

The relevance of the melting phase in the foundry process has been evidenced in Mitterpach et al. (2017b) too, who did not include in the analysis the raw material acquisition phase and thus concluded that melting is the most impacting phase of the foundry process. Again, the comparison of the results of this study with the ones of Mitterpach et al. (2017b) is complex since the cast iron production phases considered in Mitterpach et al. (2017b) are different from the ones of the present study: for example Mitterpach et al. (2017b) separated the moulding and the core production phases that are instead aggregated in this study. Moreover, Mitterpach et al. (2017b) show only the EndPoint reults obtained from the Recipe v.1.1 LCIA method without differentiating the

"Climate change" impact category from the Recipe Endpoint categories.

Finally, Finkewirth et al. (2022) investigated the carbon footprint of different melting technologies for cast iron production. The study concluded that the cupola furnace has higher greenhouse gasses emissions with respect to the rotary and the electric furnaces. On the contrary in the present study Foundries F and J, which have cupola furnaces, are the ones showing the lowest scores for the category "Climate change" (Table 6). However, the authors evidenced that the result depends on the country electricity mix. In fact, as underlined by Torielli et al. (2014) when electricity comes primarily from fossil fuels fired power plants, electric induction furnaces consume more energy than cupolas for melting iron.

4.4. Final considerations and recommendations to stakeholders and impact of the study on the surveyed plants

Based on the findings described in Sections 4.1 and 4.2, possible measures to reduce the environmental impact of the foundry process could be identified. Given the fact that raw material acquisition is the most impacting phase in all the surveyed plants, the first option to increase the sustainability of cast iron production implies the decreasing of the score of the input materials.

The substitution of a relevant amount of pig iron with valid alternatives such as iron scrap and waste ductile iron where possible without significantly altering the final product quality, could be a viable solution to increase the sustainability of the production process, as demonstrated by the lowest environmental performances of foundries F, J, I and B, which already employ high quantities of iron scrap in their processes. This substitution would reduce the impact on the "climate change" and "resource use – minerals and metals" impact category.

Pig iron could also be substituted with steel scrap, taking into account the different carbon content of steel with respect to the pig iron. The substitution requires to perform specific metallurgic evaluations to understand the behavior of the new material in the foundry's furnace. However, the option has several advantages, such as the increase of the circularity of the production process and the independence of the plant from pig iron suppliers.

Moreover, given the high environmental score associated with ferroalloys, the use of recycled elements could also help in decreasing the environmental impact of the foundries where those elements have a crucial role, especially on the category "resource use – minerals and metals". The substitution of Nickel and Molybdenum with recycled elements could be achieved in two ways: the first foresees the use of iron scrap containing high quantities of the two elements, thus participating to a recycling chain; the second is the separation at the foundry site of the waste ductile iron based on the type of ferroalloys contained. Both the options imply the execution of a series of tests to understand the behavior of the recycled materials inside the furnace and a consequent modification of the cast iron production process of the foundry. Graphite can be also retrieved from recycled elements.

Further research on the effectiveness of such measures in reducing the environmental footprint of cast iron should be performed; a sensitivity analysis to understand the most efficient option is recommended. Furthermore, future research should also propose a comparison between the Italian context here described and the environmental footprint of cast iron production in other countries.

Moreover, the practices described in Stefana et al. (2019) as "management practices" could also play an important role in decreasing the environmental impact of foundries. Even if the study of Stefana et al. (2019) has been conducted only on companies equipped with electric induction furnaces, the implementation of all those practices aiming at monitoring, measuring and controlling energy and fuel consumption, implementing energy management systems, using programs and software for modelling and simulating the production process, performing regular environmental monitoring and audits and applying for environmental certifications (such as the "Made green in Italy") is necessary to move towards a more sustainable foundry process.

Finally, the present work derives from Assofond's close collaboration with its associates and Italian universities. In fact, the association representing Italian foundries has actively promoted a better understanding of the ecological transition among its associates, which are typically (with some exceptions) small and medium enterprises, that do not undertake the path towards sustainability if let alone. This has led to:

(1) significant investments in the self-production of energy from renewable sources and, above all, the creation of synergies for the construction of large-scale plants and the participation in regional or national programs;
(2) collaboration with companies that collect scrap to increase the share of recycled material: this implies improving the selection of materials, distinguishing the type of alloy, improving quality analyses, expanding the recycling of waste at the end of its life for example by extracting metals and alloys from waste of electric and electronic equipment;
(3) creation of sustainability paths, which are not only internal, but also include the company's supply chain since enterprises started asking suppliers to monitor and reduce their environmental footprint with the aim of providing customers a more sustainable product.

Finally, these initiatives also allow companies to anticipate the possible changes in the EU regulatory system on environmental issues such as the Corporate Sustainability Reporting (CSRD) Directive (that foresees the disclosure of information on the risks and opportunities arising from social and environmental issues, and on the impact of companies activities on people and the environment), the implementation of the Carbon Border Adjustment Mechanism Regulation (the EU's tool to put a fair price on the carbon emitted during the production of carbon intensive goods that are entering the EU) and the acceptance of the Taxonomy on Sustainable Finance in investments (EU Regulation 852/2020 and Acts Delegates).

All the described activities are leading to a significant growth in investments and employment potential of foundries and, since a high share of those employed in the plants are immigrants (estimated at least 40 %) there is also a contribution in the processes of integration of foreigners in Italy.

5. Conclusion

This study investigated the environmental impact of the foundry process in Italy collecting data directly from ten plants (indicated with letters from A to J). The product environmental footprint of the casts manufactured at the ten plants was estimated through the life cycle assessment technique, employing the Environmental Footprint v.3 LCIA method.

The impact categories over which the foundry process impacts more are climate change, particulate matter, resource use (minerals and metals), fossil fuels use and ecotoxicity – freshwater. In all the considered plants these five impact categories account for at least 70 % of the total impact.

In all foundries the most impacting phase is represented by the raw material acquisition. Pig iron is the input material of the foundry process that contributes most to the total impact in the major part of the surveyed plants, except for foundry C, where the majority of the impact is caused by ferroalloys and other metals. Besides pig iron, other relevant sources of impact are: the electricity used for melting in the foundries employing electric furnaces, the ferroalloys and the metals such as nickel, antimony and molybdenum.

The reduction of these impacts is challenging because it implies the substitution of pig iron and ferroalloys with recycled inputs, which is not easy since requires relevant changes in the furnace management and the implementation of research projects on how to use the recycled inputs.

Further research on the effectiveness of such measures in reducing the environmental footprint of cast iron is recommended as well as an investigation on the environmental footprint of cast iron production in contexts different from the Italian one.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available upon reasonable request for academic use and within the limitations of the provided informed consent by the corresponding author upon acceptance. Every request for raw and analyzed data and materials will be evaluated by the companies involved in the study.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2024.03.005.

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