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A comparative environmental assessment of the cast iron and steel melting technologies in Germany

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ABSTRACT

Energy transition as a response to climate change requires structural transformation in the industrial sector. While some industries have already gained the attention of research studies due to their high production and emissions levels, there is an obvious lack of analyses on small but energy intensive sectors such as casting industry. Herein, the aim of this paper is to fill this knowledge gap by implementing an environmental assessment of the cast iron and steel melting technologies.

The carbon footprint of four main types of furnaces and their variants have been determined. Moreover, sensitivity analyses have been conducted to quantify the impact of energy sources and electricity-mix. The analyses show the major differences between the environmental performances of melting technologies. As the GHG emissions depend on the adopted technology linked with specific amounts and sources of energy, the current technologies are associated with high carbon footprints (especially cupola furnaces). Therefore, reaching carbon neutrality necessitates fundamental changes in terms of types of furnaces and related energy sources.

Keywords: environmental assessment, carbon footprint, energy transition, energy-intensive industries, cast iron and steel, melting technologies

1. INTRODUCTION

1.1 Energy transition and casting industry

Energy transition brings about major challenges for the industrial sector. Due to the wide range of several industries with diverse processes already existing, there is no single universal solution that can fit all industrial activities. Each industry has to find its own suitable pathways to operate carbon-free. Some industries have already gained plentiful attention in the research activities such as steel and cement, while other smaller sectors have been relatively overlooked.

The German foundry industry consumes 4.2 TWh electricity, 2.5 TWh of foundry coke, 1.7 TWh of natural gas and 0.1 TWh of fossil fuels for cast iron and steel production, which directly and indirectly is responsible for 3.3 Mt CO_2 eq. As a result, the industry is under pressure to reduce its energy consumption and associated GHG emissions. Nonetheless, there is an obvious research gap in terms of the environmental performance of the casting technologies.

Against this background, the aim of this investigation is to compare the various melting technologies currently in practical use for cast iron and steel materials in respect of their environmental performance. Therefore, greenhouse gas emissions that are directly or indirectly linked to the provision and usage of energy are of particular interest. The comparison of these results should then form the basis for understanding the possibilities of decreasing the carbon footprint and suggesting measures to achieve carbon neutrality by 2045.

The paper is structured as follows; the different melting technologies are firstly presented in the coming section (1.2). Thereafter, the methodology and results are presented (sections 2 and 3). Finally, conclusions and outlook are presented (section 4).

1.2 Melting technologies

In literature, there are different approaches to categorize the existing furnace types. The typical

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criterion applied is the energy source, which can be classified into fossil or electric. Alternatively, the type of production (i.e. continuous or batch) [1]. The cast material or the design of the furnace chamber is also used as criterion [2].

As there are metallurgical and operational differences between iron and steel casting, different furnace types are usually used for the two materials. The dominant furnace types for cast iron are cupola and induction furnaces [3, 4, 5]. The rotary kiln is also suitable, but is rarely used in Germany [3, 6, 7]. Induction and crucible furnaces are used for transportation and maintaining warmth. In Germany, only electric arc and induction furnaces are used for steel casting [7, 3, 4]. Crucible furnaces are also used for transportation and maintaining warmth [7].

The cupola furnace is one of the two standard furnace types for the production of liquid cast iron. In terms of structure, it consists of shaft (vertical) furnace with a collecting hearth (inside or outside the furnace), a burner system at the lower end and a material charging system at the top [7]. There are various variants of cupola furnace (e.g. cold-blast, hot-blast and coke-free cupola furnaces), which influence the carbon footprint due to the different material and energy inputs.

Rotary drum furnaces are used to melt small and medium-sized quantities of scrap or raw material for cast iron materials [8]. The special feature of this type of furnace is the rotation of the entire furnace body around its longitudinal axis. This rotational movement achieves several beneficial operational effects; the constant movement ensures optimal homogenization of the furnace contents [1]. Moreover, the energy and heat transfer are improved, so that shorter melting times and better energy utilization are achieved [9].

As second standard furnace for liquid cast iron, the **induction furnace** consists mainly of a ceramic refractory container, a copper coil and a steel frame [10]. The induction furnaces' mode of operation differs significantly from cupola furnaces; an AC voltage is applied to the coil, and the resulting flow of current then generates an electromagnetic field in the inner area of the coil, which surrounds the container with the charge. Hence, currents are induced in the conductive melting material by the electromagnetic field [8, 11].

Finally, **Electric arc furnaces** which can be used in different ways as a melting unit are employed in both the iron and steel casting industry [7, 5] . Its basic structure consists of a furnace vessel including a lid, a support arm with electrode(s) and a hydraulic tilting device [7]. In the interior of the furnace vessel, a refractory lining is applied in the lower area, (i.e. the hearth) as well as on the hinged lid. Water cooling for all relevant components, such as side walls and lid, means that there is no need for a full lining with refractory material and at the same time improves the furnace properties [12].

2. MATERIALS & METHODS

The subject of this investigation is the melting technologies, more specifically all energy and material flows that are necessary for their operation. This also includes flows for auxiliary and ancillary units such as cooling and ventilation, which are not directly necessary for melting, but without which the operation of the furnaces is not possible. For all these parameters, with the exception of the raw material, the emissions of scopes 1 to 3 are taken into account (i.e. including power production and transportation of energy inputs such as coal).

The system boundary thus encloses all activities and materials that are required directly or indirectly for the melting and runs directly at the respective melting unit, as shown in Fig. 1. As far as the literature allows, the geographical consideration is limited to Germany and North Rhine-Westphalia as a representative industrial center. For carbon footprint analyses, the standards of DIN EN ISO 14067, 14040 and 14044 have been used [13, 14, 15].

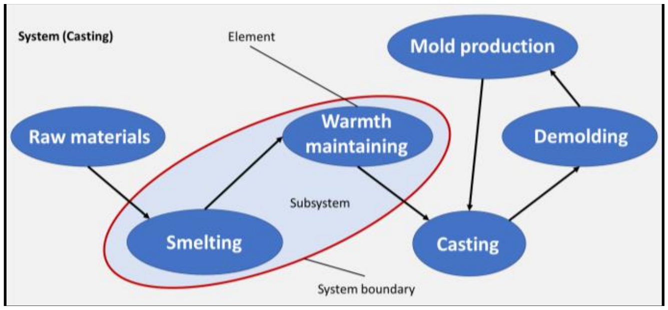

Fig. 1 System boundary

To permit the comparability with other studies, the functional unit is defined as the one-time melting of one ton of casting material ready for casting from the corresponding raw material. All material and energy flows required for the production of the functional unit are taken into account except the raw material. The raw material has been omitted due to the wide range of cast products and specifications. Consequently, several compositions of primary and secondary raw materials are used in the industry, which can be very challenging to be classified within few categories. Therefore, the analyses focus on the melting technologies, including the main energy and material flow.

Examples of fluxes considered are coke (cupola furnace), electricity (induction and electric arc furnace) and the consumption of refractory material in the respective furnace lining. For modelling and calculating the carbon footprint, OpenLCA is used with background data of EcoInvent database. In accordance with the availability and topicality of the EcoInvent database, the time horizon corresponds to the most current data records stored and retrievable. Herein, the electricity mix of 2020 in Germany was considered.

The key figures used for the modeling are the result of extensive literature research. The data inventory and the references are annexed to the paper as a supplementary information (table 1). In order to ensure the completeness and validity of the data obtained in this way as best as possible, they were recorded redundantly if possible and checked and verified in their magnitude by experts.

3. RESULTS

The carbon footprints of the analyzed melting technologies are depicted in Fig. 2. The cold-blast copula furnace has the highest carbon footprint (i.e. 683.5 kg CO_2 eq./ton product), of which the production and combustion of coke represent approximately 85%. The hot-blast copula furnace has roughly the same environmental impact due to the same structure, inputs and outputs. As it is more efficient in terms of energy consumption, the third type of copula furnace (i.e. hot blast + lining) has a lower carbon footprint than the first two types (541.6 kg CO_2 eq./ton product).

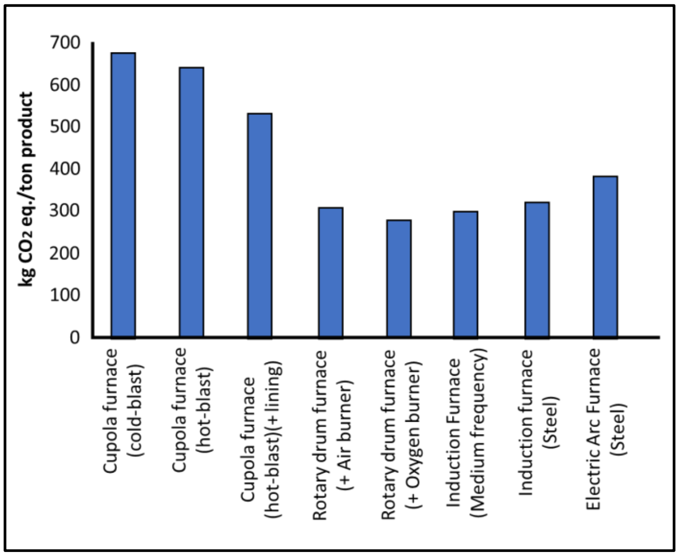

Fig. 2 Carbon footprints of melting technologies

The second main category (i.e. rotary drum furnace) is associated with approximately half of the cupola furnace's carbon footprint. The first type (i.e. air burner) is associated with 311.7 kg CO_2 eq./ton product, which can be mainly attributed to the natural gas consumption. Although the second type (i.e. oxygen burner) uses significantly lower amounts of fossil fuels, its carbon footprint is roughly equal due to the emissions associated with oxygen production.

For the electric-based smelting technologies, the carbon footprint is mainly attributed to the electricity production (i.e. scope 2 emissions). Melting cast iron and steel in the induction furnace is associated with 347.1 and 372.2 kg CO_2 eq./ton product respectively. In addition to the major contribution of power production, the usage of coal and natural gas also contribute to the carbon footprint of the Electric Arc Furnace (total = 424 kg CO_2 eq./ton product).

To depict the influence of the electric energy source on the environmental impact, a sensitivity analysis has been conducted on the carbon footprint of induction and electric arc furnaces. The electricity mix in France is representative for an intensive use of nuclear energy and the Swedish electricity mix has the highest renewable energy share in Europe. Hence, the electricity mixes of these two countries are applied to classify the impact of alternative generation mixes.

The effect of the composition of the electricity mix on the greenhouse potential is significant, also with regard to the fossil fuels used. Italy and Germany both have a comparable share of fossil fuels in their energy mix [16]. Although the total share of coal and gas is approximately the same in both countries, the almost four-times higher share of coal in Germany has a significant impact on greenhouse gas emissions. Fig. 3 shows clearly that assuming the Italian electricity mix results in 100 to 120 kg less CO_2 eq. than applying the German electricity mix. According to the above results, up to 93% of the emissions can theoretically be saved if large parts of nuclear power are used as in France or electricity from renewable energies according to the Swedish model.

In [7], the Federal Environment Agency recommends the use of oxygen as a primary measure to reduce energy requirements and CO_2 emissions. In order to avoid relocation effects within the value chain, this measure is examined via sensitivity analysis on the environmental impact of the rotary drum furnace. As shown in Fig. 4, the results reveal that the reduction in natural gas consumption by using oxygen compensates the oxygen production's additional emissions.

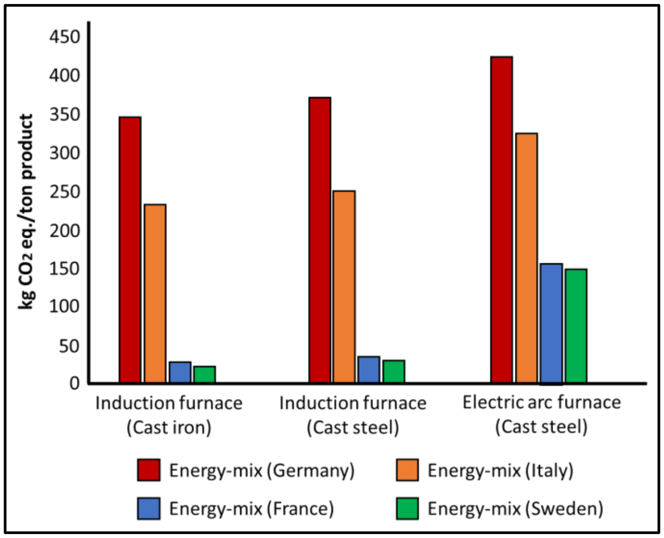

Fig. 3 The impact of energy-mix on the carbon footprint

From a technical perspective there is also the possibility of using hydrogen instead of natural gas as energy carrier for rotary drum furnaces. This approach is already being investigated and implemented in practice [17]. Equivalent to the procedure in cupola furnaces, natural gas is replaced by approximately 3.3 times the amount of hydrogen to bring the same total energy conversion into the melting process [9].

Again, a sensitivity analysis has been conducted to examine the saving effects of hydrogen in the greenhouse gas emissions, while using two burner variants (i.e. air and oxygen burners). From an environmental point of view, the usage of air burners for hydrogen firing is preferable compared to oxygen burners. The production of the required oxygen results in two times higher greenhouse gas pollution compared to the use of air burners. While the application of oxygen burned is suitable for natural gas based rotary drum furnaces, this measure counters its ecological intention if switching the energy carrier towards hydrogen.

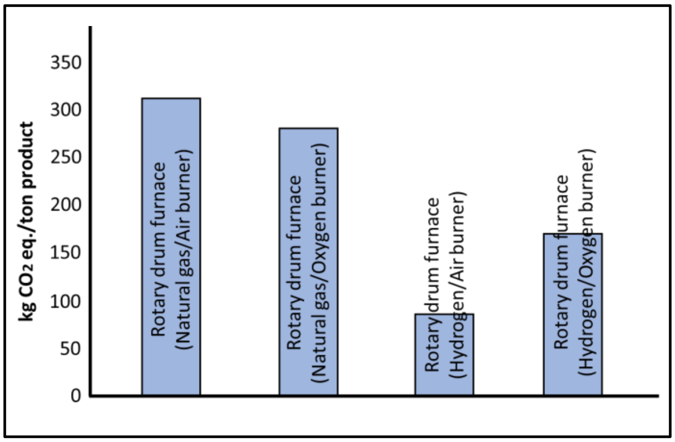

Fig. 4 The impact of energy source on the carbon footprint of rotary drum furnaces

4. CONCLUSIONS & OUTLOOK

The analyses illustrate the main differences between the melting technologies in terms of the carbon footprint. As discussed, cupola furnaces are associated with the highest carbon footprint, which can be attributed to the usage of coke. Although electric-based melting technologies have lower environmental impact, they still indirectly emit considerable amounts of GHG emissions due to the current electricity-mix in Germany. Herein, the analyses highlight the importance of considering a holistic perspective to ensure that the environmental impact is not relocated to other upstream or downstream areas (e.g. electricity, refractory, oxygen production and input materials).

Based on the preceding sections, the GHG emissions of the melting process are basically dependent on the adopted technology and the main energy carrier. In the short term, increasing energy efficiency can contribute in decreasing the GHG emissions. This goal can be achieved via two routes; either minimizing the specific energy input or maximizing the amounts of outputs (e.g. by waste heat recovery and combined heat and power).

Nevertheless, energy efficiency measures cannot achieve the needed significant GHG reductions in long term. Radical changes in the energy sources as well as in the melting technologies will be required to decarbonize the sector. Taking into account also non-environmental aspects the technology with the lowest carbon footprint cannot be always considered as the most suitable solution. From a technical perspective, there is a high number of products with different characteristics and one single technology cannot suit all the applications. From an economic perspective, the sector is highly fragmented and characterized by low-profit margins [18]. Hence, more analyses are needed in order to define the optimum strategy for each category of producers and products besides the ecological aspects.

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Supplementary Information

Table1: Data inventory

Furnace	Input		Output		References
	Material & Energy	**Magnitude**	**Material & Energy**	**Magnitude**	
Cupola furnace (cold blast)	Coke	130 kg/t	Cast iron	1000 kg	[20] [7] [21] [9] [22][3] [8] [23] [24] [25][26] [27] [28] [29]
	Blast	600 m^3/t	Slag	45 kg/t	
	Oxygen	24 m^3/t	Dust	11.5 kg/t	
	Electricity	20 kWh/t	CO_2	450 kg/t	
	Natural gas	2 m^3/t	SO_2	0.86 kg/t	
	Refractory material	4.8 kg/t	NO_x	0.09675 kg/t	
	Limestone	39 kg/t	CO	10.93 kg/t	
	Raw material	1035 kg/t			
	Warmth maintaining	60 kWh/t			
Cupola furnace (hot blast) (+ lining)	Coke	100 kg/t	Cast iron	1000 kg	
	Blast	500 m^3/t	Slag	60 kg/t	
	Oxygen	6 m^3/t	Dust	8 kg/t	
	Electricity	30 kWh/t	CO_2	350 kg/t	
	Natural gas	2 m^3/t	SO_2	0.06 kg/t	
	Refractory material	6 kg/t	NO_x	0.09 kg/t	
	Limestone	30 kg/t	CO	2 kg/t	
	Raw material	1035 kg/t			
	Warmth maintaining	60 kWh/t			
Cupola furnace (hot blast)	Coke	125 kg/t	Cast iron	1000 kg	
	Blast	520 m^3/t	Slag	60 kg/t	
	Electricity	30 kWh/t	Dust	9 kg/t	
	Natural gas	2 m^3/t	CO_2	438 kg/t	
	Refractory material	1.5 kg/t	SO_2	0.075 kg/t	
	Limestone	37.5 kg/t	NO_x	0.1125 kg/t	
	Raw material	1035 kg/t	CO	2.5 kg/t	
	Warmth maintaining	60 kWh/t			

Rotary drum furnace (+ Air burner)	Natural gas	115 m^3/t	Cast iron	1000 kg	[7] [9] [26] [27] [30]
	Blast (air)	1092.5 m^3/t	Slag	40 kg/t	
	Raw material	1035 kg/t	Dust	1.6 kg/t	
	Refractory material	11 kg/t	CO_2	230 kg/t	
			SO_2	0.06 kg/t	
			NO_X	0.35 kg/t	
			CO	1.25 kg/t	
Rotary drum furnace (+ Oxygen burner)	Natural gas	56.25 m^3/t	Cast iron	1000 kg	
	Oxygen	144 m^3/t	Slag	40 kg/t	
	Raw material	1035 kg/t	Dust	1.6 kg/t	
	Refractory material	11 kg/t	CO_2	112.5 kg/t	
			SO_2	0.06 kg/t	
			NO_X	0.1712 kg/t	
			CO	0.6114 kg/t	

Induction furnace (iron)	Electricity	530 kWh/t	Cast iron	1000 kg	[31] [26] [5] [11] [7] [9] [32] [33] [34] [35] [24] [36] [35] [27]
	Raw material	1035 kg/t	Slag	10 kg/t	
			Dust	0.5 kg/t	
	Auxiliary units	15.9 kWh/t			

Induction furnace (steel)	Electricity	560 kWh/t	Cast steel	1000 kg	[37] [34] [38] [7] [10][39] [24] [26]
	Raw material	1035 kg/t	Slag	15 kg/t	
	Refractory material	3.25 kg/t	Dust	0.5 kg/t	
	Auxiliary units	16.8 kWh/t			

Electric arc furnace	Electricity	450 kWh/t	Cast steel	1000 kg	[40] [41] [12] [24] [42] [43] [44] [45] [46] [47] [48] [49] [7] [50] [51] [52] [53] [54] [55] [56] [57] [58] [59] [60] [61] [62] [63] [64] [65] [66]
	Blast (air)	133.88 m^3/t	Slag	100 kg/t	
	Oxygen	36 m^3/t	Dust	18.8 kg/t	
	Coal	20 kg/t	CO_2	80 kg/t	
	Natural gas	6 m^3/t	SO_2	0.105 kg/t	
	Refractory material	4 kg/t	NO_X	0.237 kg/t	
	Electrode	1.1 kg/t	CO	16.25 kg/t	
	Lime	22.5 kg/t			
	Dolomite lime	15 kg/t			
	Raw material	1050 kg/t			
	Cooling	13.5 kWh/t			