Slag volume effects on DRI-based electric furnace steelmaking

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ABSTRACT

A likely increasingly important pathway for future low-carbon ironmaking and steelmaking is the combination of gas-based direct reduction with electric furnace steelmaking (DRI-EAF route), or with electric smelting (DRI-ESF route). In the DRI-EAF route, the gangue that is present in the iron ore is fluxed and removed as slag in the melting (steelmaking) step. This is in contrast with integrated steelmaking, in which the gangue is removed as part of blast furnace ironmaking. For DRI-EAF steelmaking, the amount and composition of slag depend on the iron ore composition, flux additions, and iron yield. Slag volume and composition affect phosphorus removal, foaming behavior, and the process energy requirements. In this work, heat data from a year of DRI-EAF production was analyzed to test whether the expected relationship between slag volume and electricity consumption for EAF steelmaking was observed. The data include slag analyses (one sample per shift), and heat-level information on all inputs, final steel temperature and dissolved oxygen concentration, electricity consumption, tapped steel mass, and tap-to-tap time. In analyzing the data, the slag volume was estimated from the assayed slag CaO concentration, and CaO inputs to the EAF. The expected effect of slag volume on steelmaking energy consumption was calculated with a mass and energy balance, considering the heat of mixing of the slag. The calculated energy requirement of slag formation is in line with previous estimates reported in the literature.

INTRODUCTION

Gas-based direct reduction is expected to become an increasingly important ironmaking route, since it could utilize green hydrogen to produce iron from ore with low or zero carbon dioxide emissions. The direct-reduced iron (DRI) product retains the impurities (mainly gangue oxides and phosphorus) that are present in the ore feed; these impurities need to be removed as slag during subsequent melting or electric arc furnace (EAF) steelmaking. Currently, relatively high-grade pellets (total iron concentration > 67%) are mainly used to produce DRI to serve as EAF feed (Kim and Sohn 2022); in comparison, blast furnace pellets typically contain 63-65% Fe (Poveromo 1999). As the globally consumed tonnage of pellets for DRI increases, the availability of high-grade pellets is expected to become a constraint for DRI-EAF production (Barrington 2022).

DRI that is produced from lower-grade pellets can be used in EAF steelmaking, but with disadvantages due to the increased slag volume (mass of slag relative to steel mass): the disadvantages include the increased energy consumption (to heat and melt the slag), lower iron yield (more iron lost to the slag), the production of more by-product, and lower production rate (because of the higher electricity requirement). Already in 1980 effects of increased DRI used in EAF steelmaking were noted – in particular, the increased electricity consumption related to slag formation (Kishida et al. 1980). In addition, the release of acidic gangue from DRI during the initial part of the heat, before lime and doloma fluxes have dissolved, tends to cause the formation of acidic slag, leading to attack on the refractory lining of the furnace (Song et al. 2020). If lime additions are insufficient to maintain a high slag basicity when melting DRI with acidic gangue, poorer dephosphorization results (Heo and Park 2018).

In this work, data from an operating plant that utilizes a high proportion of DRI in EAF steelmaking was used to test whether the expected effects of slag volume on electricity consumption, iron yield, and power-on time are observed. Details of the plant operation and data are summarized in the next section, followed by analysis of the data and comparison with the theoretically expected trends.

PLANT DETAILS

The plant uses a mixture of scrap and cold DRI as metallic feed, with lime and doloma as fluxes. Natural gas is used in oxyfuel burners, and additional oxygen is injected. The DRI contains around 2% carbon (by mass); additional carbon is fed through the top of the furnace, and also injected. Data from one year of production was analyzed. Slag analyses were recorded approximately three times per day, resulting in data for around 800 heats (after removing missing analyses). Out of these, “pour back” – return of steel from secondary metallurgy to the EAF – occurred during 16 heats.

DRI compositions were available for the year of production, but were not related to specific heats in the analysis presented here. The variability in the gangue content of the DRI was taken to be the main cause of changes in slag volume. The DRI analysis reported the mass percentages of carbon, metallic iron, and oxidic iron (taken to be FeO); the balance of the DRI was assumed to be gangue.

The distributions of DRI compositions for the year of production are given in Figure 1. The median DRI composition was 2.2% carbon, 90.3% total iron, 83.2% metallic iron, and 5.3% gangue (calculated value).

The main metallic input is DRI (Figure 2), with the scrap input accounting for about 40% of the tap mass on average.

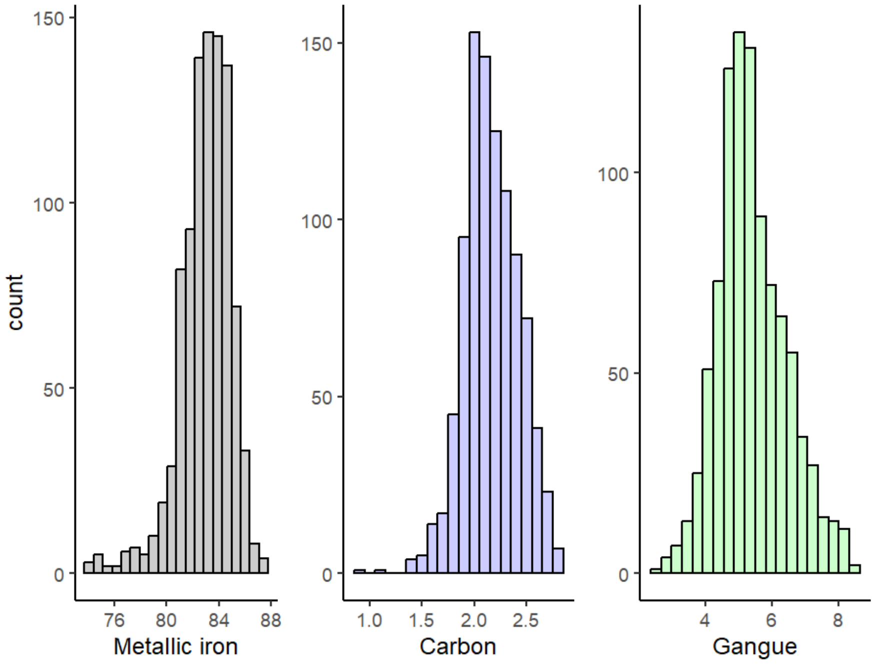

FIG 1 – Distribution of DRI compositions (mass percentages)

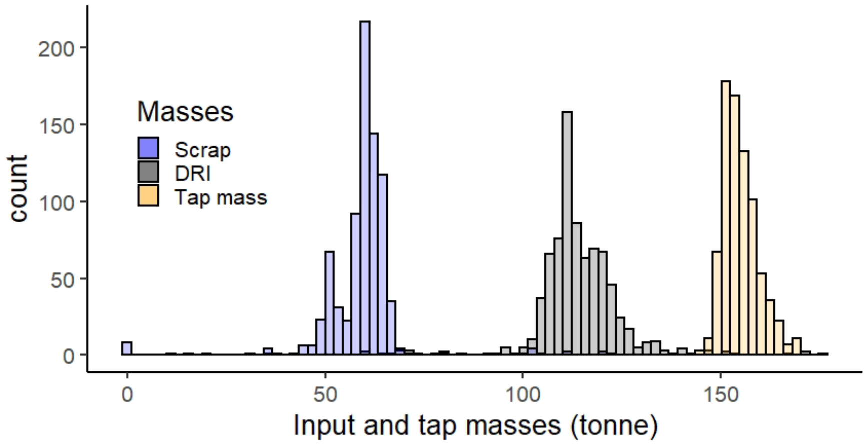

FIG 2 – Steel input and tap masses.

The power-on time was around 50 minutes (Figure 3), with a wider range of tap-to-tap times. The power during arcing was near the median value of 95 MW for all the heats (Figure 4). The slag volume was estimated from the (%CaO) in the slag, and additions of lime and doloma. (The average slag composition is given in Table 1.) In this calculation, it was assumed that the only sources of CaO were the fluxing additions, and that the lime was pure CaO and the doloma pure stoichiometric CaO.MgO. The calculated slag volume varied significantly between heats (Figure 4), allowing evaluation of the effects of slag volume from the recorded data. The Fe yield (also shown in Figure 4) was estimated from the tap mass of steel (approximated as 100% Fe), the scrap mass (also taken to be 100% Fe), and the DRI input (using the median total Fe in DRI of 90.3%). In some cases the calculated iron yield was greater than 100%, likely reflecting variations in the amount of steel retained in the furnace between taps, as a hot heel. Similar values for the Fe yield were found using the analyzed iron concentration in the slag, the calculated slag volume, and the tap mass of steel: both approaches gave median Fe yields of 95.3%.

The reported concentration of iron in the slag likely includes a contribution of entrained metallic iron. One mechanism for iron entrainment is incomplete settling: the DRI is top-fed into the furnace, requiring the iron to travel through the slag layer before reaching the metal bath. However, because information on the metallic iron concentration in the slag was not available, in these calculations all the iron in the slag was taken to be oxidic.

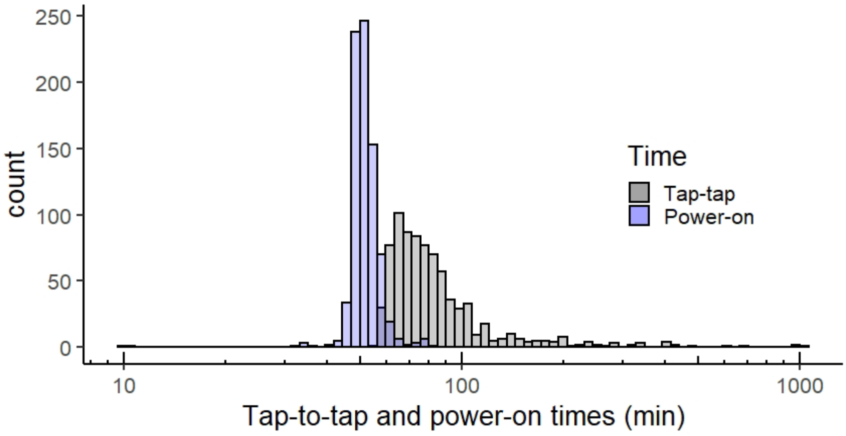

FIG 3 – Distribution of tap-to-tap and power-on times.

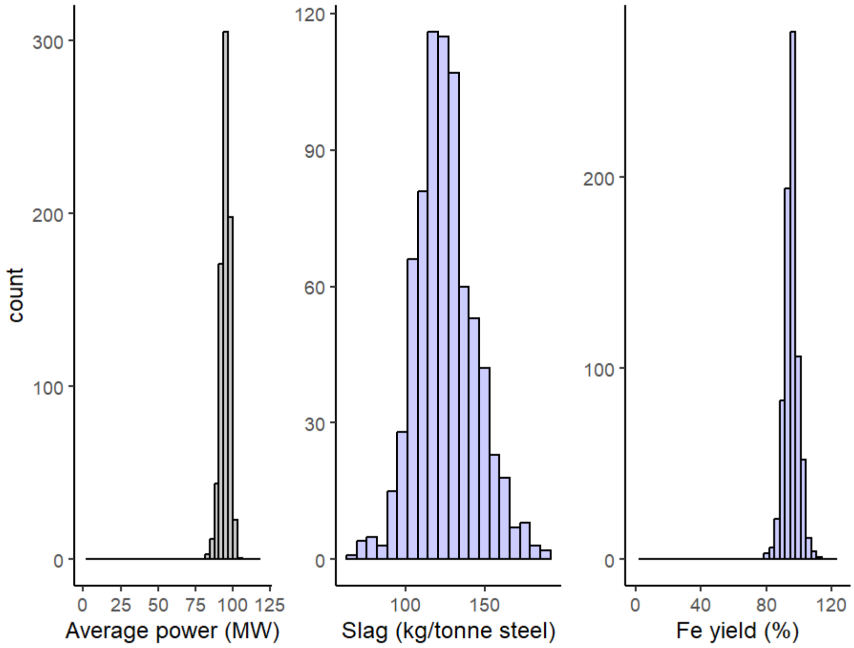

FIG 4 – Furnace power during arc heating, with the calculated slag volume and Fe yield.

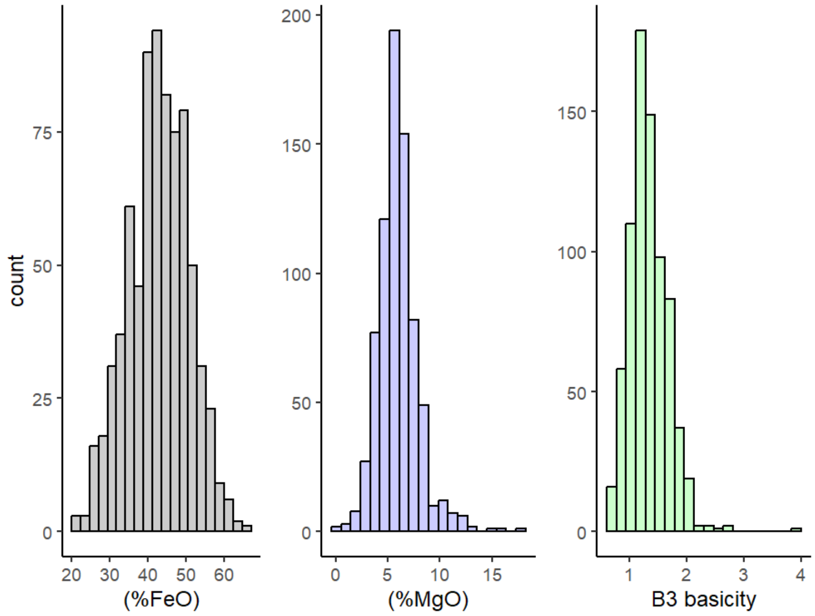

FIG 5 – Slag composition parameters: iron content, percentage MgO, and B3=(%CaO)/(%SiO_2+%Al_2O_3).

TABLE 1 – Average slag composition (mass percentages).

%CaO	%SiO_2	%MgO	%Al_2O_3	%MnO	%"FeO"	B3*
24.0	14.2	5.99	4.93	2.39	42.9	1.33

*B3 = (%CaO) / (%SiO_2 + %Al_2O_3)

FITTED AND EXPECTED TRENDS

Correlations of electricity consumption, power-on time and iron yield are shown in Figure 6. Before fitting these trends (and plotting the data) outliers were removed using the approach of Iglewicz and Hoaglin ('NIST/SEMATECH e-Handbook of Statistical Methods (NIST Handbook 151)' 2020) to account for measurement and reporting errors; the total number of heats removed as outliers was 51 out of a total of 808. In Figure 6, the lines are separate linear fits to each of these correlations, with the slopes of the lines reported in Table 2. While the R^2 values of the correlations are low, the small P values do indicate significance, and the fitted slopes are close to the theoretically expected values, as discussed below.

The expected slopes were calculated as follows: The effect of slag volume on energy consumption was estimated from the estimated average oxide composition of DRI. In the absence of detailed DRI analyses, it was assumed that the relative masses of SiO_2, Al_2O_3 and MnO in the DRI were the same as in the slag (that is, it was assumed that the main source of these species in the slag was the DRI). The ratio of FeO to gangue (SiO_2, Al_2O_3 and MnO) in the DRI was found from the DRI analyses. The required additions of CaO and CaO.MgO were calculated from the analyzed MgO/CaO ratio in the slag, and the B3 basicity value. The resulting mass balance (for 1 kg additional slag mass) is summarized in Figure 7. As this figure indicates, the composition of the additional slag that is estimated using this approach is similar to the average slag composition of Table 1.

For the energy balance, the input species were taken to be the simple compounds listed in Figure 7. To calculate the enthalpy of the slag, the heat of mixing of the liquid slag (relative to pure oxides) was based on a slag thermodynamics model (Björkvall et al. 2001). Based on this energy balance, the heat transfer required to melt and heat 1 kg of slag to 1600 °C was estimated as 0.55 kWh/kg. This is close to the value of 0.53 kWh/kg mentioned in the classic study of the effects of DRI on EAF steelmaking (Rigaud et al. 1976). In comparison, the fitted slope was 0.78 kWh/kg.

TABLE 2 – Fitted and expected effects of changes in slag volume on electricity consumption, power-on time and Fe yield.

Output variable	**Units**	**Theor. coeff.**	**Fitted coeff.**	**Std. error**	**Units of coefficient**	R^2	***P* value**
Electricity	kWh/tonne	0.55	0.78	0.06	kWh / kg slag	0.19	$<2\times10^{-16}$
Power-on time	min	0.076	0.075	0.006	min / (kg slag / tonne steel)	0.17	$<2\times10^{-16}$
Fe yield	%	-0.031	-0.038	0.008	% / (kg slag / tonne steel)	0.03	1.2×10^{-6}

The expected effect of slag volume on the power-on time was calculated by using the observed relationship between the slag volume and electricity consumption (0.78 kWh/kg slag), together with the median power during arcing (95 MW); this gave an expected increase of 0.076 minutes for every 1 kg/tonne increase in slag volume. The observed slope was nearly the same, at 0.075 min/(kg/tonne) (Table 2).

The effect of slag volume on iron yield was estimated by assuming that the slag composition would remain unchanged with increases in slag volume. (Figure 4 does show that the relative variation in slag volume is much greater than the variation in the iron concentration in the slag.) The yield is then given by the steel tap mass, divided by the sum of the tap mass and the mass of iron in the slag:

$$\text{Yield} = (100\%) / [1 + (W_{slag}/W_{Fe}^{tap})(\%\text{Fe})_{slag}/100],$$

where W_{slag} is the slag mass, W_{Fe}^{tap} is the tap mass of steel, and $(\%\text{Fe})_{slag}$ is the iron concentration in the slag. This dependence was well approximated by a linear relationship between yield and slag volume, for values of the slag volume from 90 kg/tonne to 160 kg/tonne. The slope of this expected relationship is -0.031% /(kg/tonne), which is similar to the fitted slope of -0.038% /(kg/tonne) listed in Table 2.

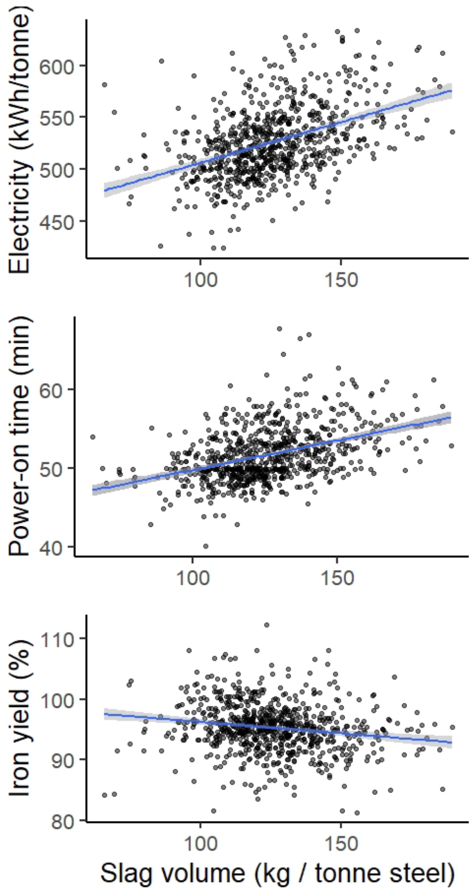

FIG 6 – Observed correlations between the slag volume, electricity consumption, power-on time and Fe yield. The lines show fitted linear relationships, with 95% confidence intervals around these lines.

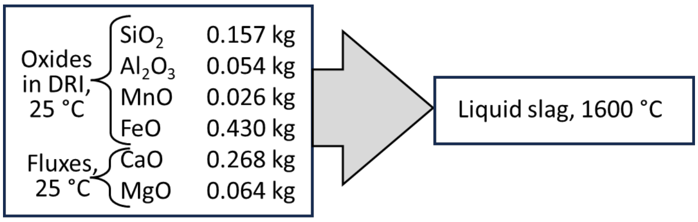

FIG 7 – Schematic of the inputs to the mass and energy balance used to estimate the effect of slag volume on EAF energy consumption.

The low R^2 value of the fitted correlation between slag volume and electricity consumption reflects the reality that several other process conditions strongly influence energy consumption. A previously fitted correlation for the electricity consumption includes tap-to-tap time, tapping temperature, and injection of oxygen and natural gas, together with variables related slag volume (DRI and flux additions) (Kleimt et al. 2005). A similar approach was tested here, using the process variables listed in Table 3. These variables differed from those used by Kleimt et al., in that the effects of DRI and flux additions were captured with the single variable of slag volume, and carbon input was added as a variable. The carbon input was the sum of top-added carbon, injected carbon, and the carbon in the DRI (calculated from the DRI mass and its average carbon concentration of 2.16%).

The coefficients from the multiple linear regression are reported in Table 4. The theoretical coefficients were calculated from mass and energy balances, with inputs and outputs as summarized in Table 5. The results of these calculations are summarized in Table 4 as the “Theoretical coefficients”. The expected effect of pour-back is equal to the enthalpy of liquid iron at 1600 °C, which is 377 kWh/tonne, similar to the previously used value of 385 kWh/tonne (Rigaud et al. 1976).

Table 4 shows that the fitted effects of slag volume, natural gas injection and carbon addition are similar to the theoretically calculated effects. Burning natural gas with oxygen decreases the electricity requirement: the natural gas burners are effective at melting scrap early in the heat. Carbon addition **increases** the electricity requirement, because the added carbon tends to reduce FeO from the slag; the reduction reaction ($C + FeO \rightarrow CO + Fe$) is endothermic. The fitted effect of tap temperature is weaker than expected, but with a relatively large *P* value. The fitted benefit of pour-back is not as strong as expected, but this is based on a small number of heats.

Oxygen injection would be expected to decrease the electricity consumption because oxidation of iron is strongly exothermic; this is the basis for the theoretical coefficient of -5.4 kWh per Nm^3 of oxygen, as listed in Table 4. However, the fitted trend is that increased oxygen injection correlates with **higher** electricity consumption. A likely mechanism is that increased oxygen injection would increase the iron oxide concentration in the slag. An increased iron oxide concentration lowers the slag foaming index (Jung and Fruehan 2000); poorer slag foaming can lead to increased heat loss to the furnace side walls, resulting in increased electricity consumption despite the exothermicity of iron oxidation.

The fitted and actual electricity consumption for all the heats is compared in Figure 8. The background shading in the figure shows the distribution of the data points. Most of the values cluster close to the median electricity consumption of 522 kWh/tonne. As noted in Table 4, half the fitted values of electricity consumption lie within 17 kWh/tonne of the actual values.

TABLE 3 – Process variables considered in multiple linear correlation for electricity consumption, with the observed ranges of the variables in the plant data.

Variable	Units	Min	Lower quartile	Upper quartile	Max
Slag	kg/tonne	65.6	113	137	189
Natural gas	Nm^3/tonne	0	0.94	1.36	2.65
Carbon	kg/tonne	12.2	23.8	28.7	39.8
Oxygen	Nm^3/tonne	13.7	19.7	22.5	27.3
Tap temp.	°C	1578	1620	1648	1714
Tap-to-tap	minutes	54.5	66.4	89.6	430
Pour-back*	tonne/tonne	0	0	0	0.32

*Only 16 heats out of 757 had non-zero pour-back amounts

TABLE 4 – Theoretically calculated effects of process variables on electricity consumption (in kWh/tonne), with the coefficients from multiple linear correlation

Variable	Theor. coeff.	Fitted coeff.	Std. error	*P* value
Slag	0.55	0.31	0.06	1.7×10^{-8}
Natural gas	-8.1	-7.9	2.7	0.0038
Carbon	3.3	3.0	0.26	$<2\times10^{-16}$
Oxygen	-5.4	4.6	0.49	$<2\times10^{-16}$
Tap temp.	0.23	0.08	0.04	0.056
Tap-to-tap	–	0.24	0.02	$<2\times10^{-16}$
Pour-back	-377	-169	44	0.00012

R^2 = 0.47; Residuals: 1st quartile -16.7 kWh/tonne; 3rd quartile 16.1 kWh/tonne

TABLE 5 - Summary of inputs and outputs used to estimate the effects of process variations on energy consumption

Case	Inputs, with temperature	Outputs, with temperature
Natural gas combustion	CH_4 and stoichiometric O_2 (25 °C)	CO_2, H_2O (1200 °C)
Oxygen lancing	Fe (1600 °C), stoich. O_2 (25 °C)	FeO (1600 °C)
Carbon injection	FeO (1600 °C), stoich. C (25 °C)	Fe (1600 °C), CO (1200 °C)
Melting DRI gangue	See Figure 7 for inputs (25 °C)	Molten slag (1600 °C)

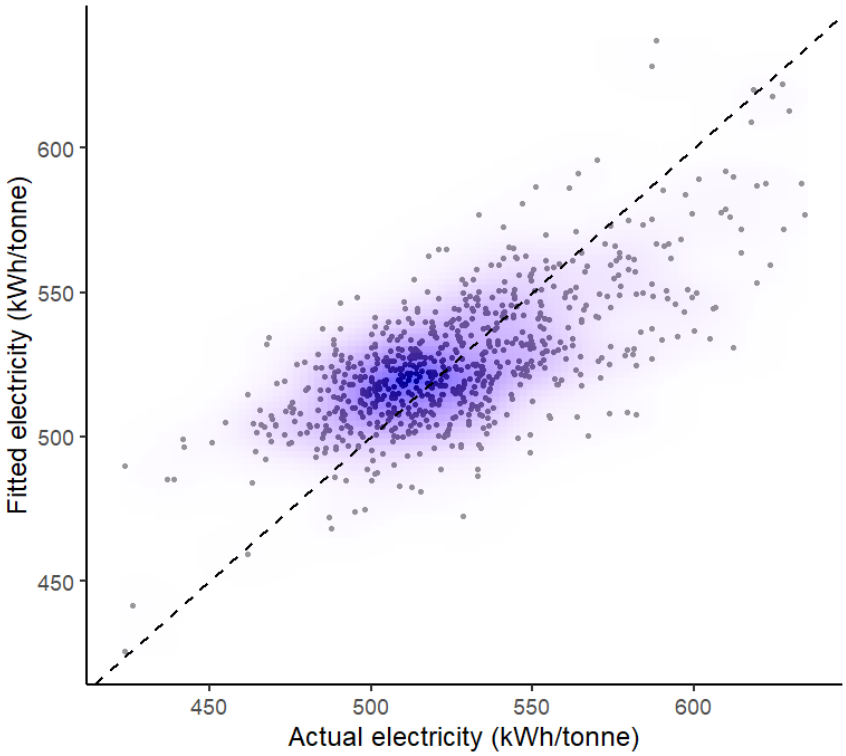

FIG 8 – Comparison of actual electricity consumption per heat, and the consumption calculated with the coefficients from the multiple linear regression. The broken line shows the 1:1 relationship, and the shading indicates the density of the distribution of points.

CONCLUSIONS

Analysis of a year's production data of an EAF plant that uses a large proportion of DRI confirmed the expected effects of the increased slag volume that would result from a higher input of gangue in DRI: Higher electricity consumption per tonne of steel, longer power-on times, and decreased iron yield. The effects of process variables on process heating requirements – from multiple linear regression – generally agree with the quantitative relationships derived from simple mass and energy balances. A notable exception is oxygen usage: For the conditions considered here, increased oxygen injection was associated with higher electricity consumption, possibly because of a negative effect on slag foaming.

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