Direct Reduced Iron Quality and Electric Furnace Steelmaking

Chris Pistorius
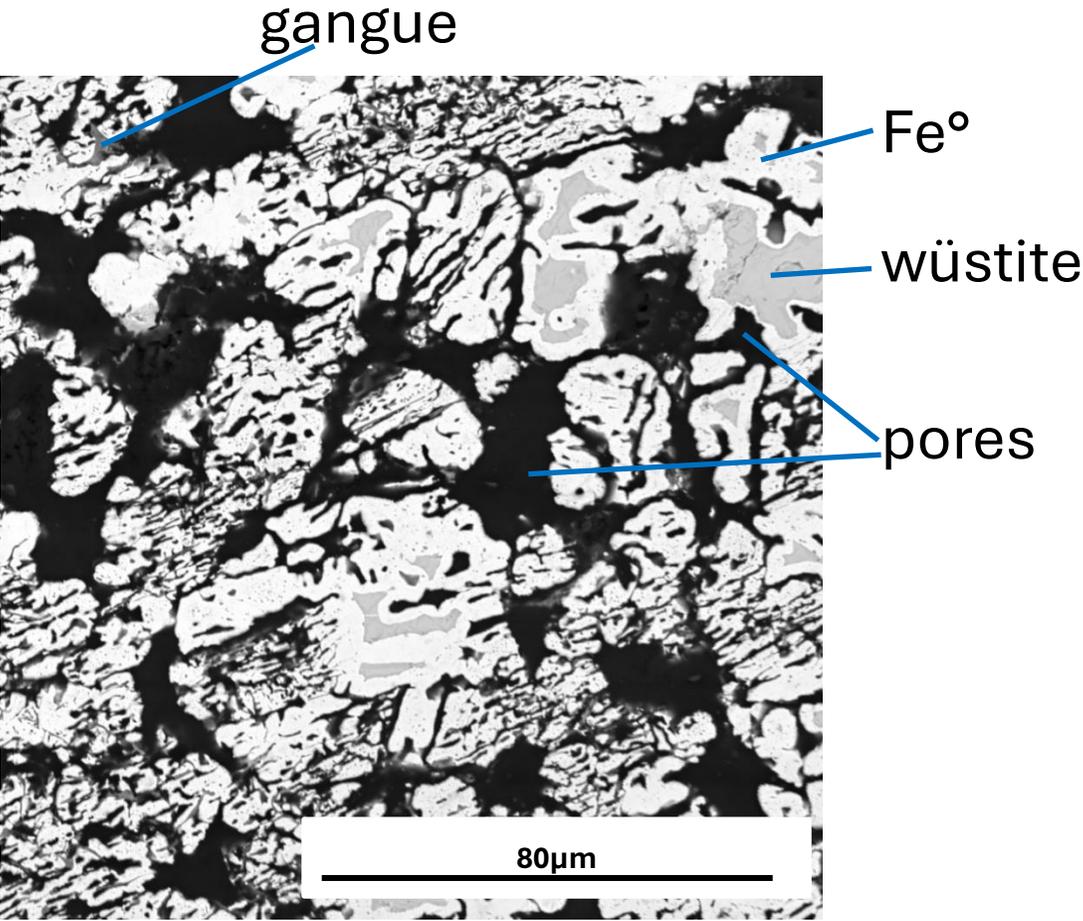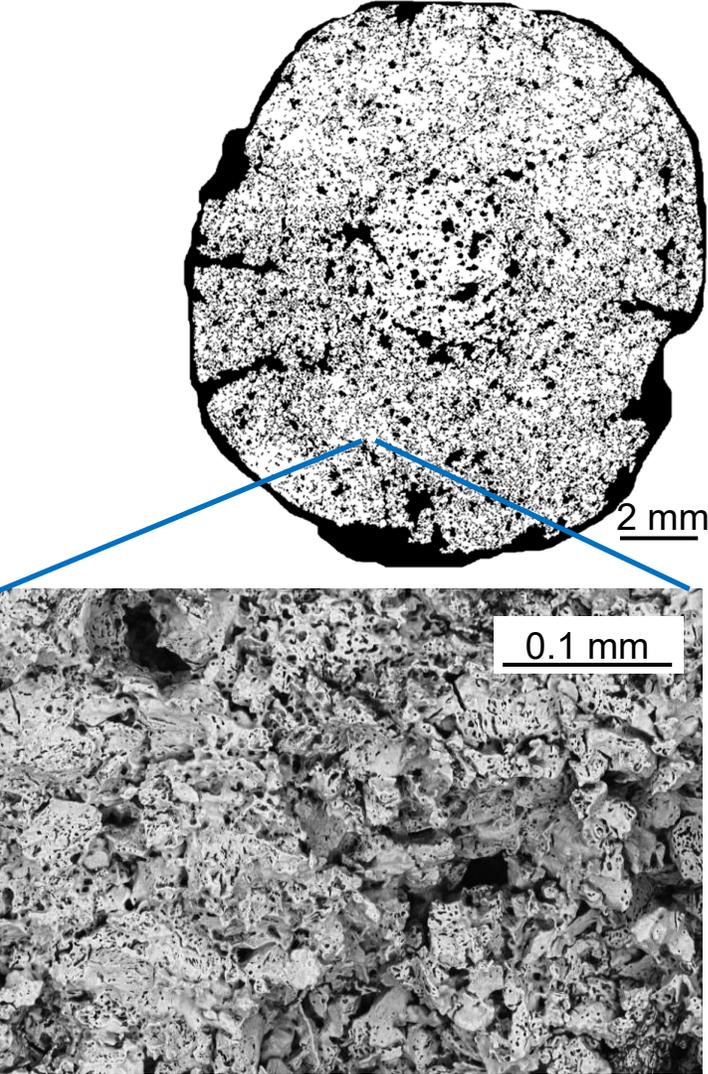
Center for Iron and Steelmaking Research

Carnegie Mellon University

Center for Iron and Steelmaking Research

MSE
MATERIALS SCIENCE & ENGINEERING
Carnegie Mellon University

Physical and chemical properties of DRI matter

gangue

Fe°

wüstite

pores

2 mm

0.1 mm

80μm

Chemical components of DRI and their role in EAF

| Component	EAF destination / role
Fe_xO (unreduced oxide)	FeO in slag
SiO_2, Al_2O_3, CaO, MgO (gangue oxides)	Slag / refractory wear
Carbon (elemental or Fe_3C)	Slag foaming; nitrogen removal
Phosphorus	Steel and slag

Example of effect of gangue in DRI:

Transient acid slag attacks refractory

Remedies:
- Fluxing
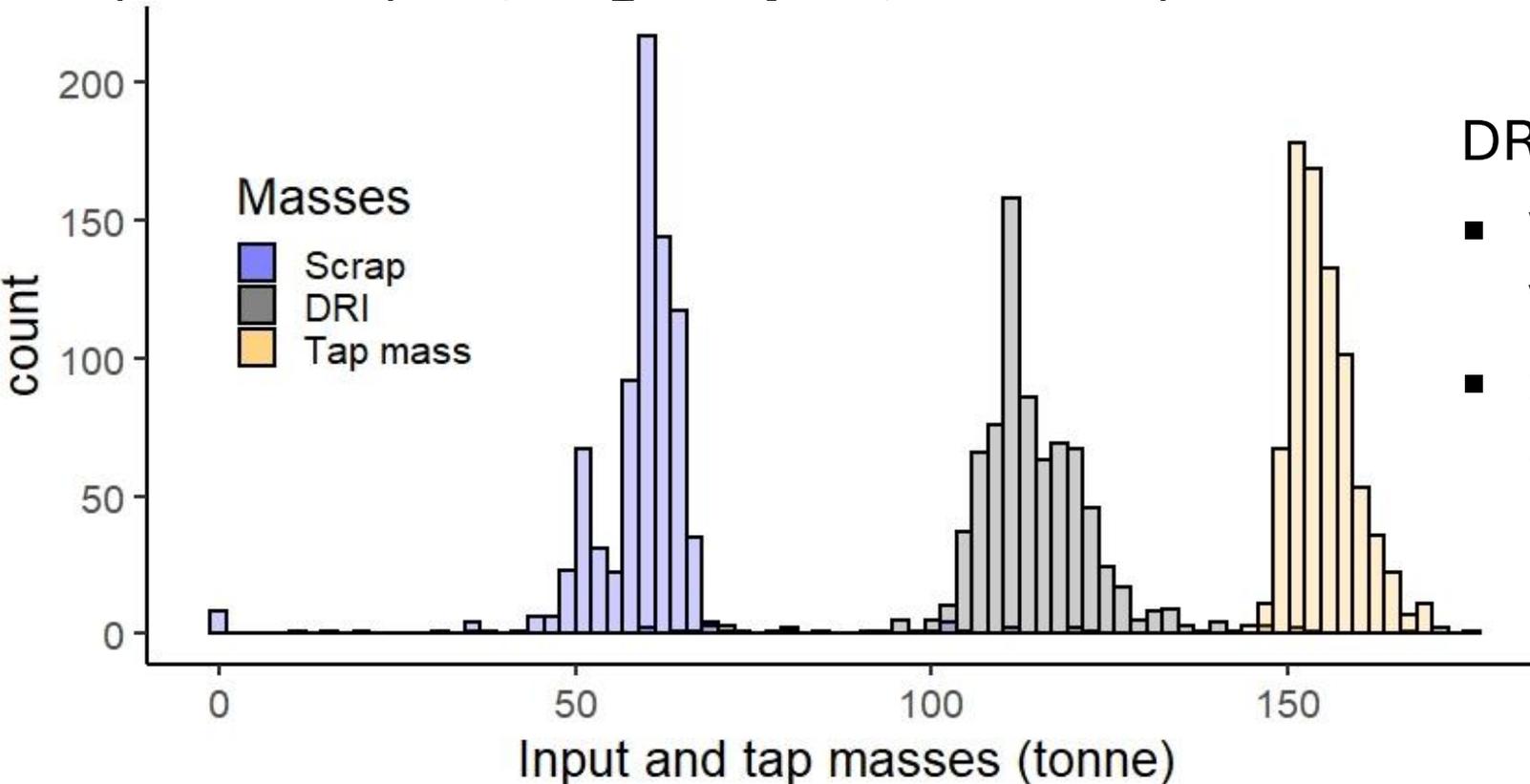- Maintaining larger slag heel

(Song *et al.*, 2020; https://doi.org/10.1007/s11663-020-01788-x)
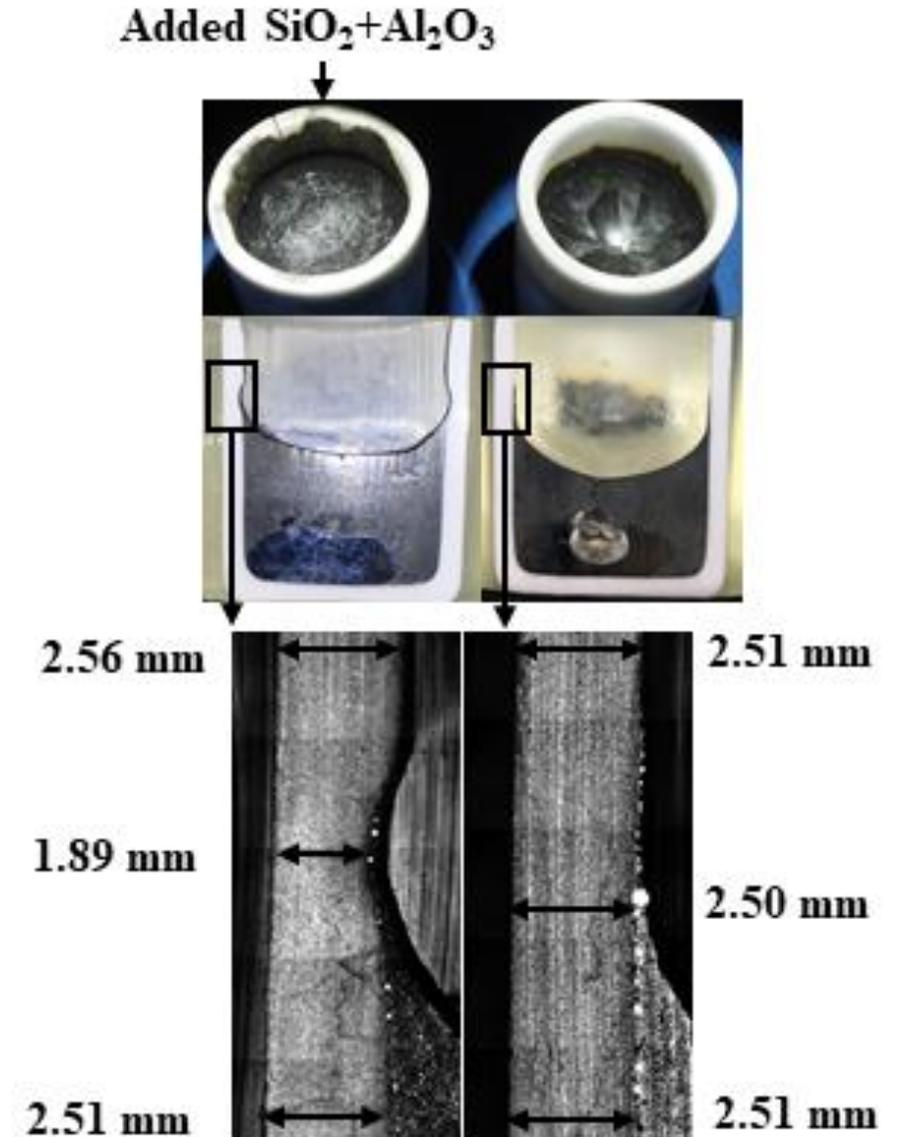
Question addressed:

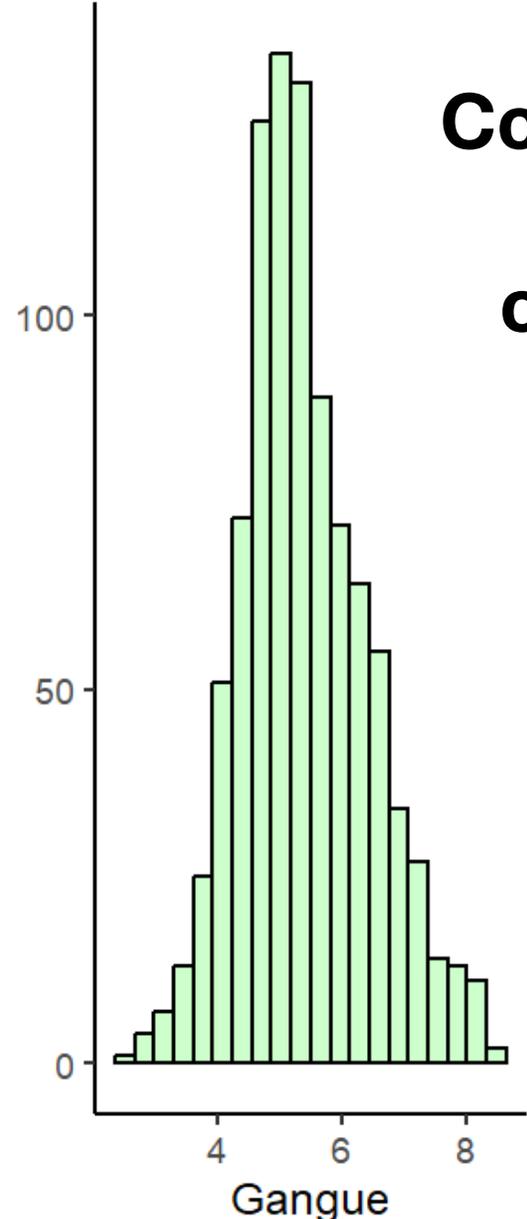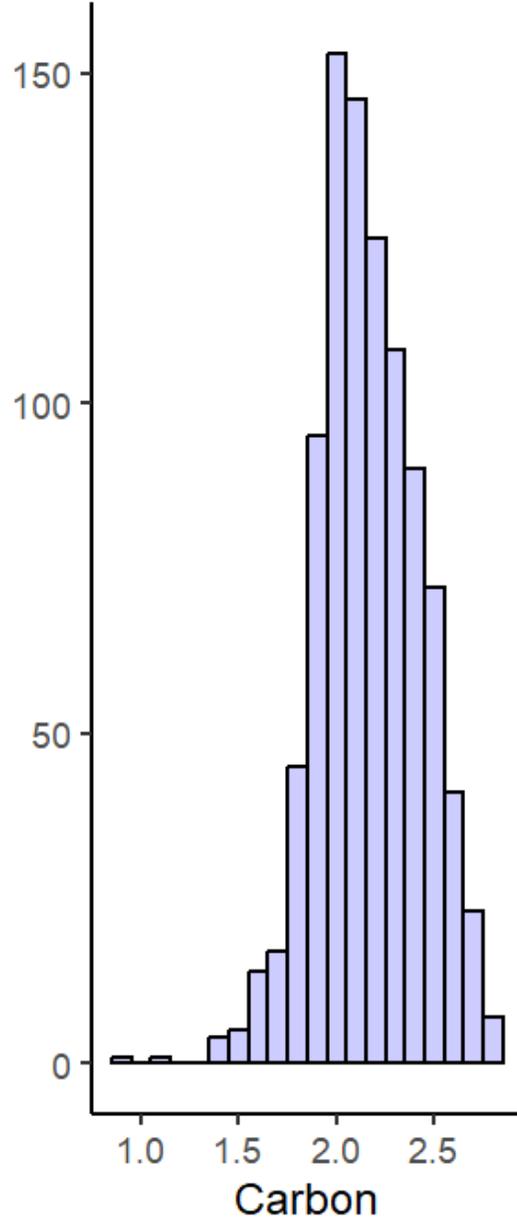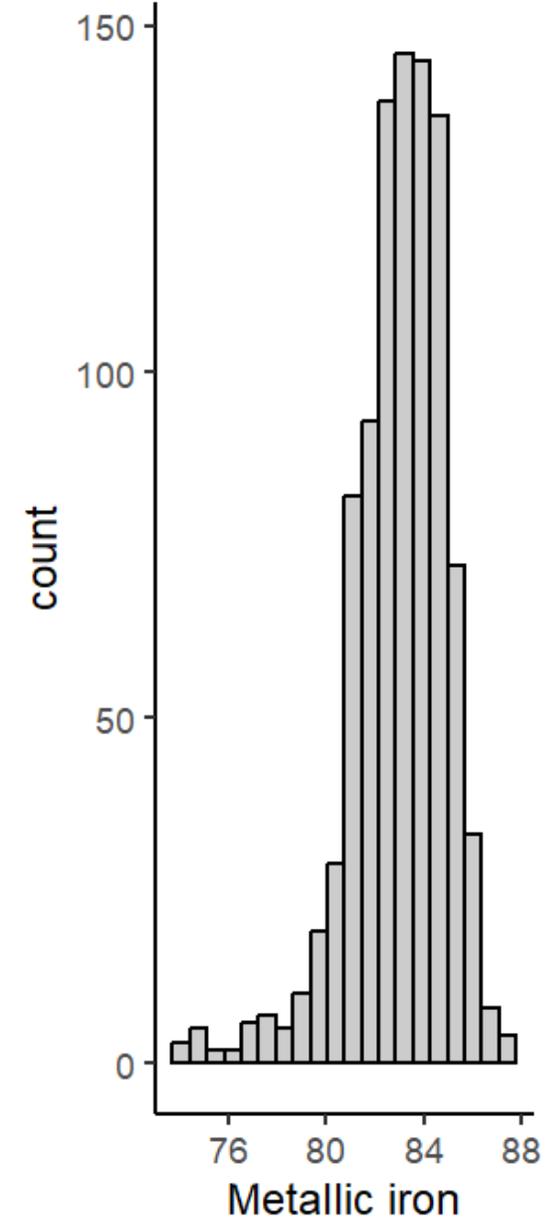## Do changes in DRI chemistry affect EAF **electricity consumption** as predicted?

1 year of heat data analyzed:
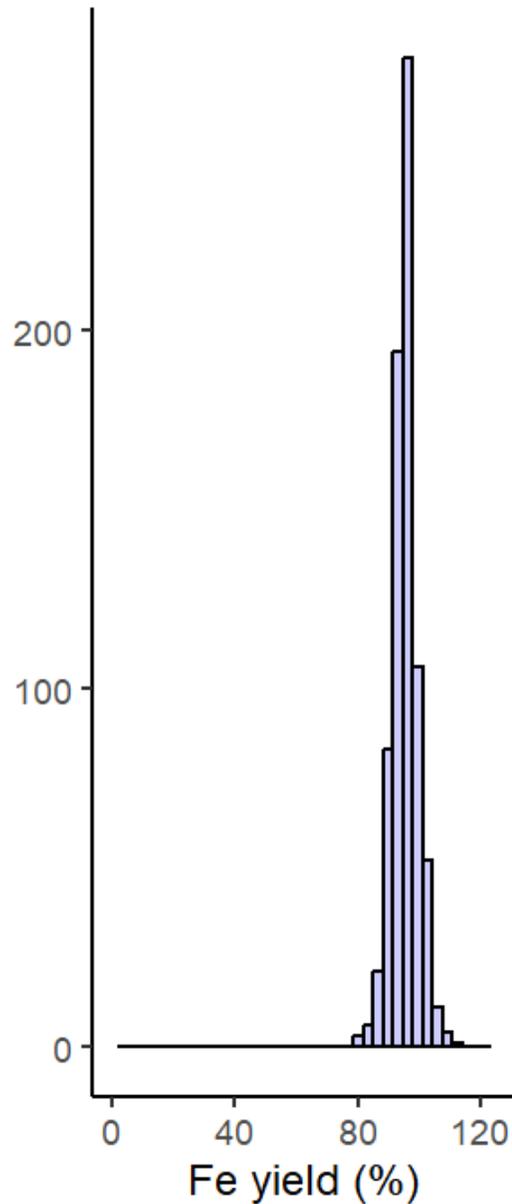All process inputs; slag analyses; steel temperature & dissolved oxygen
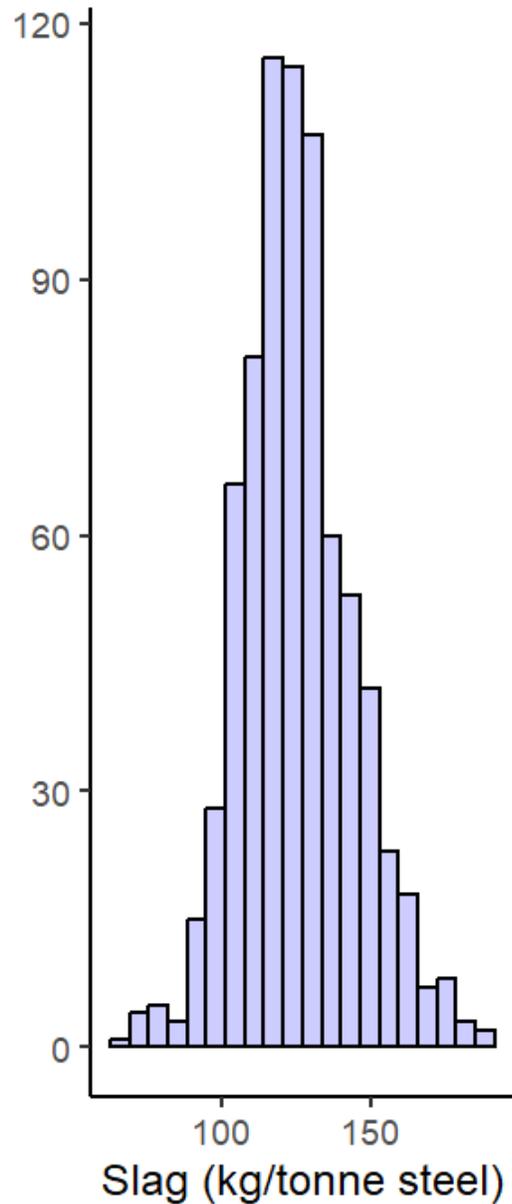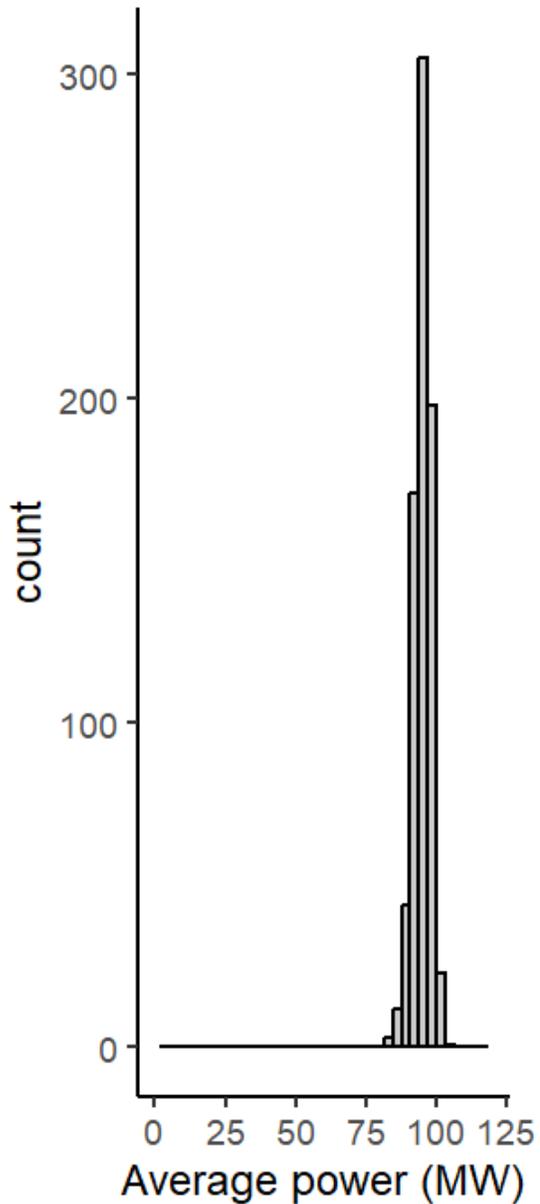

DRI is the main metallic input

- Variation in DRI affects slag volume

- Slag volume calculated from analyzed (%CaO) in slag, using masses of added lime & doloma

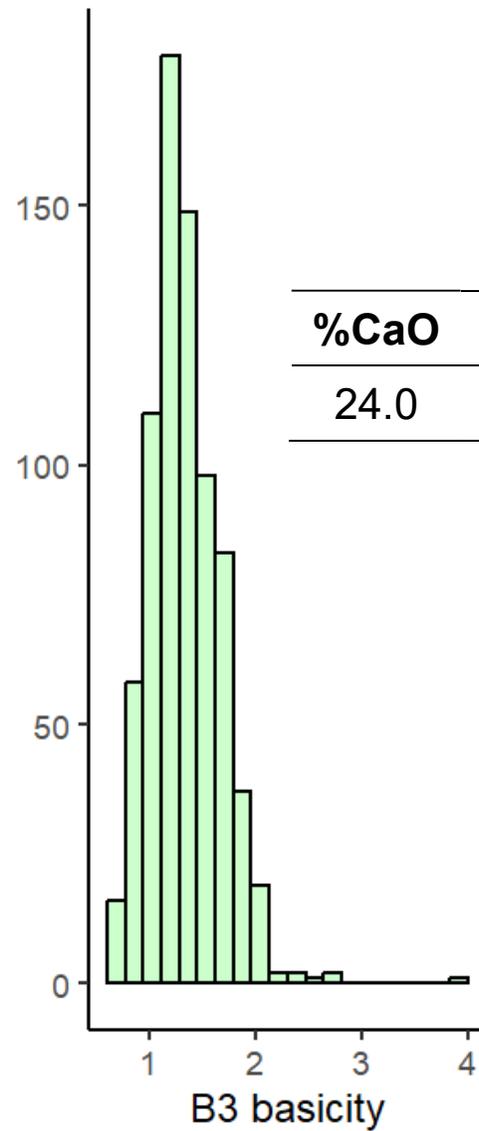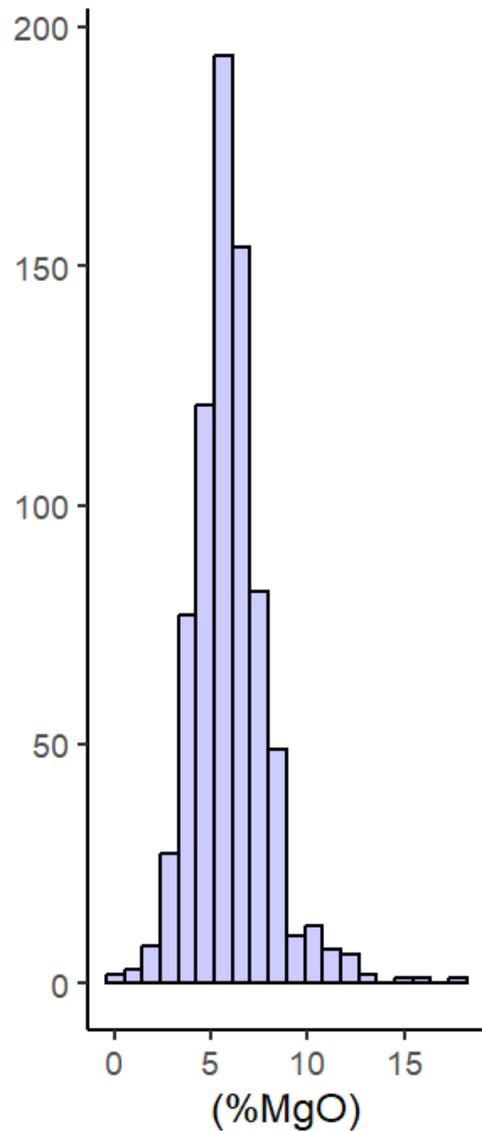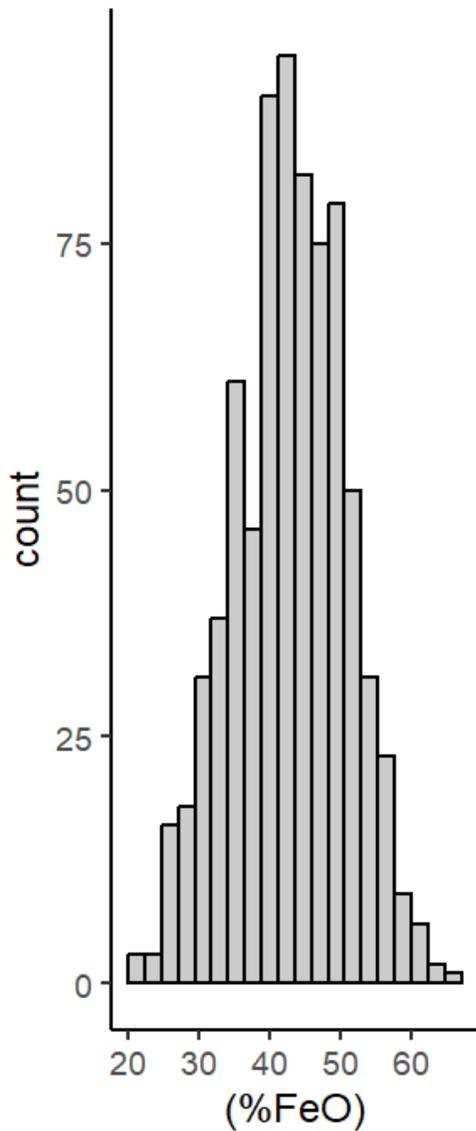**Considerable variation in gangue & carbon concentrations in DRI**

DRI compositions
(mass percentages)

Considerable variation in slag volume

Slag composition distribution

Average composition:

%CaO	%SiO$_2$	%MgO	%Al$_2$O$_3$	%MnO	%'FeO'	B3*
24.0	14.2	5.99	4.93	2.39	42.9	1.33

*B3 = (%CaO) / (%SiO$_2$ + %Al$_2$O$_3$)

XGBoost:

Machine-learning method used to fit effect of process variables (nonlinear fit to process data)

Input variables (heat basis; expressed per tonne of tapped steel):
- Carbon (mainly from DRI)
- Natural gas volume
- Lance oxygen volume
- Tap-to-tap time
- Tapping temperature
- Slag volume

Target variable: Electricity consumption (kWh/tonne)

Shapley analysis of XGBoost model:

## Quantifies marginal contribution of each feature to the model output

Q. Zhuo, M. N. Al-Harbi, and P. C. Pistorius, "Feature Engineering to Embed Process Knowledge: Analyzing the Energy Efficiency of Electric Arc Furnace Steelmaking," *Metals*, vol. 15, no. 1, p. 13, Dec. 2024, doi: 10.3390/met15010013.

More important

Less important
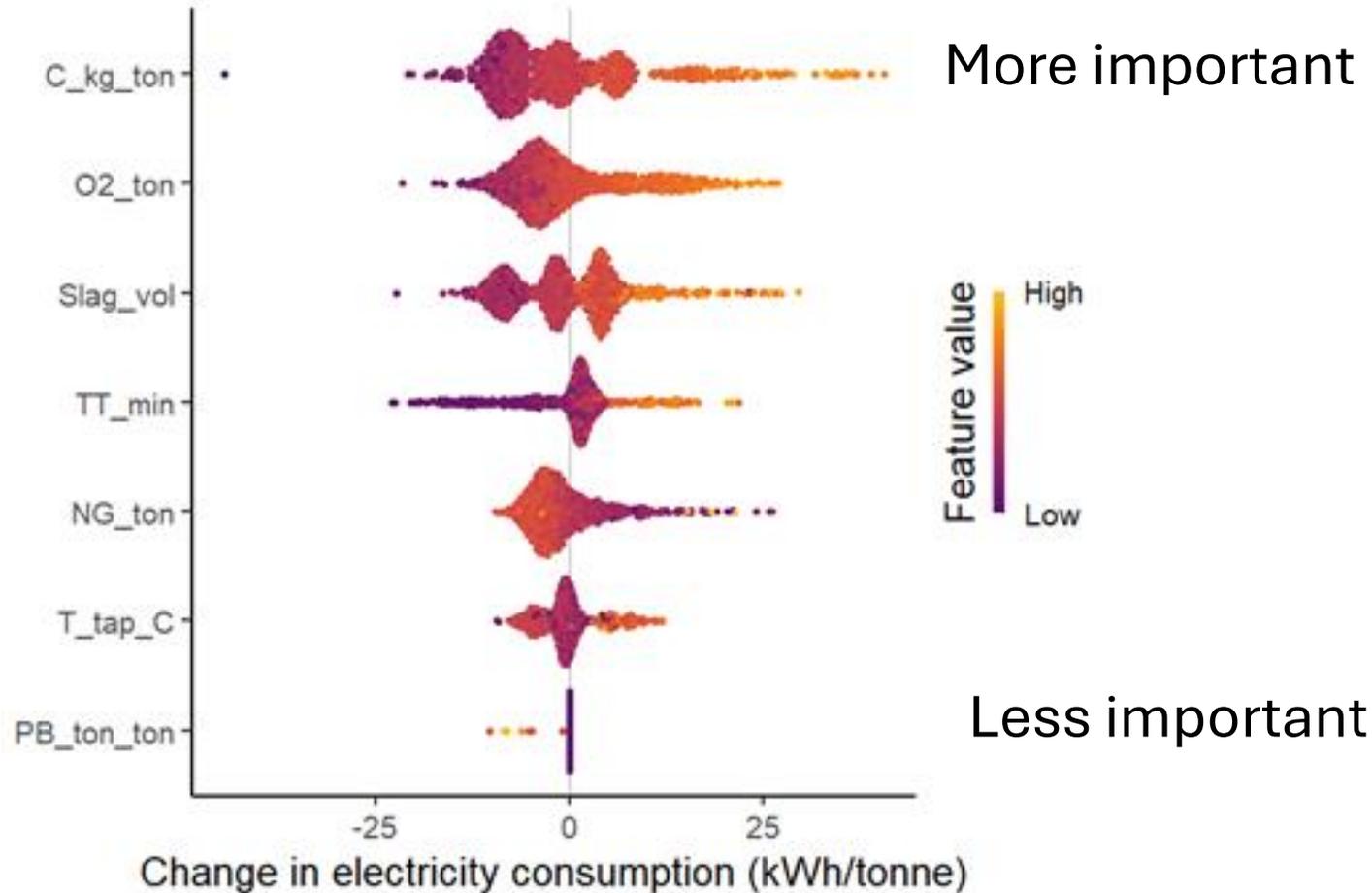
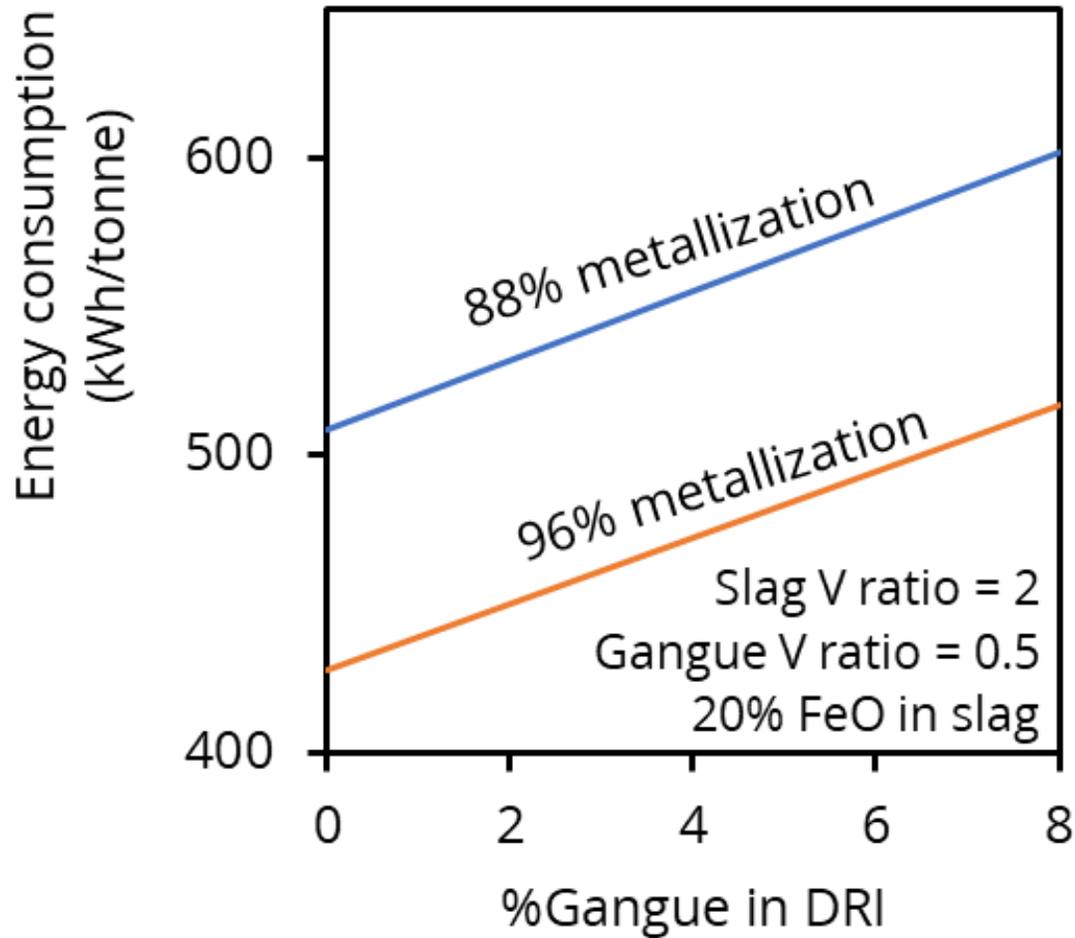# Theoretical effects of slag volume & carbon input:

Calculated with mass & energy balance

Assumption: Change in energy requirement
= change in electricity consumption
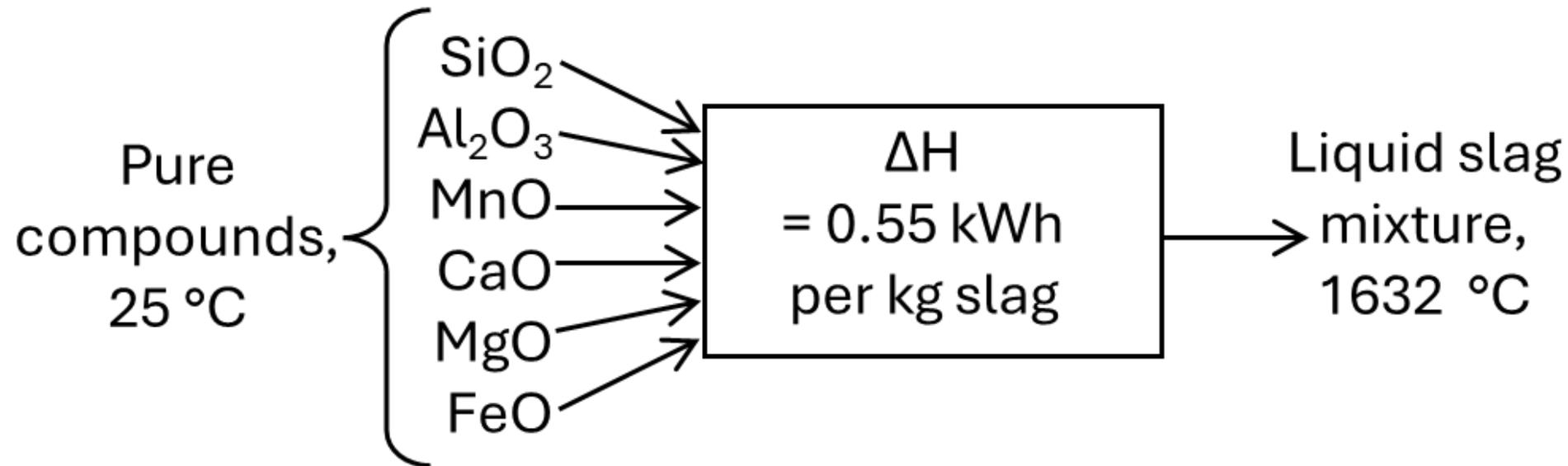
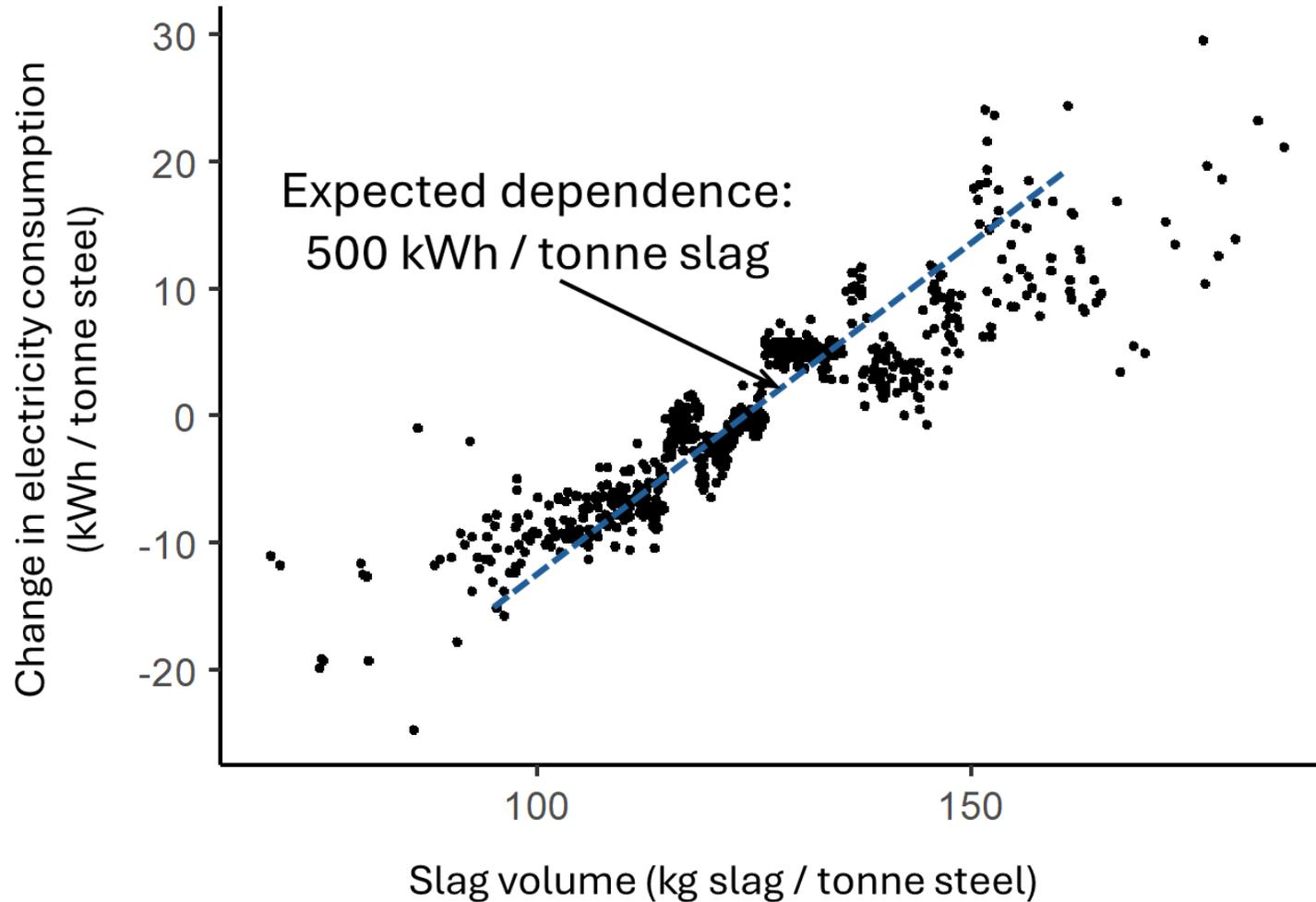**Slag volume effect**

Similar values for slag volume effect reported earlier

Turcotte, Marquis & Dancy:
"Use of direct reduced iron the electric arc furnace,"
I & SM, Volume 7, Issue 11, Pages 16-27, Nov 1980

Results of XGBoost fitting + Shapley analysis in recent work:
Higher slag volumes correlate with higher electricity consumption

Zhuo *et al.* (2024)
doi: 10.3390/met15010013.

Expected effect of carbon input on electricity consumption

For a given oxygen input:

- Injected O_2 primarily reacts with Fe to form FeO (exothermic)
- Added carbon reacts with FeO (endothermic)

C
25 °C

FeO
1632 °C

ΔH
= 3.3 kWh
per kg carbon

CO, 1200 °C
Fe, 1632 °C
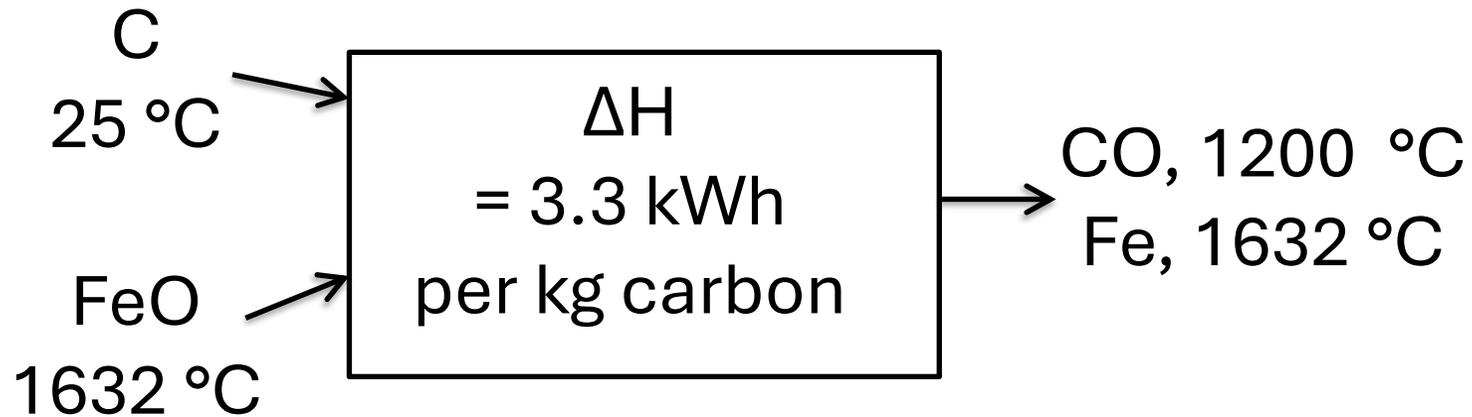
Results of XGBoost fitting + Shapley analysis:
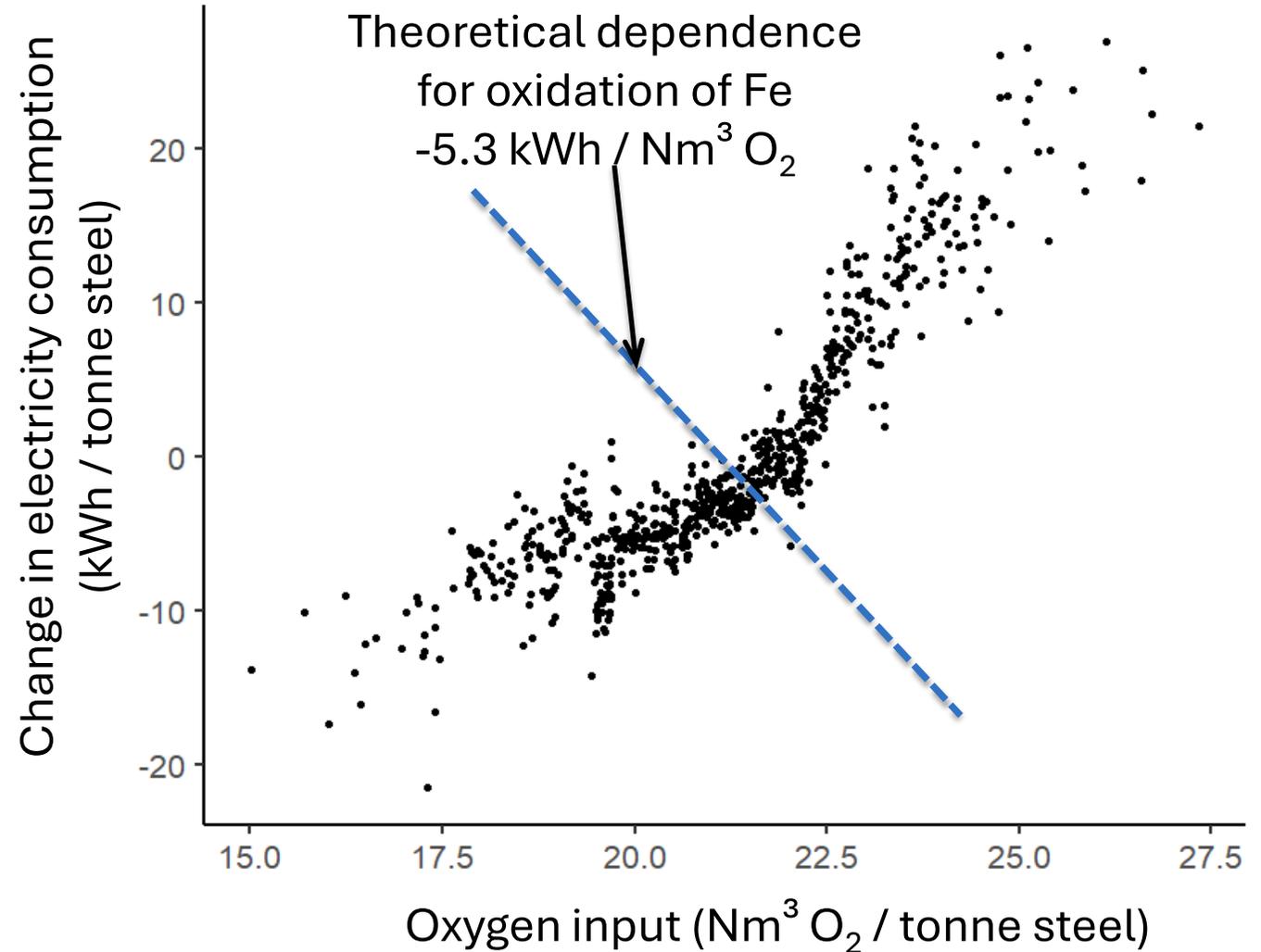Higher carbon input correlates with higher electricity consumption

Expected dependence:
3.3 kWh / kg carbon
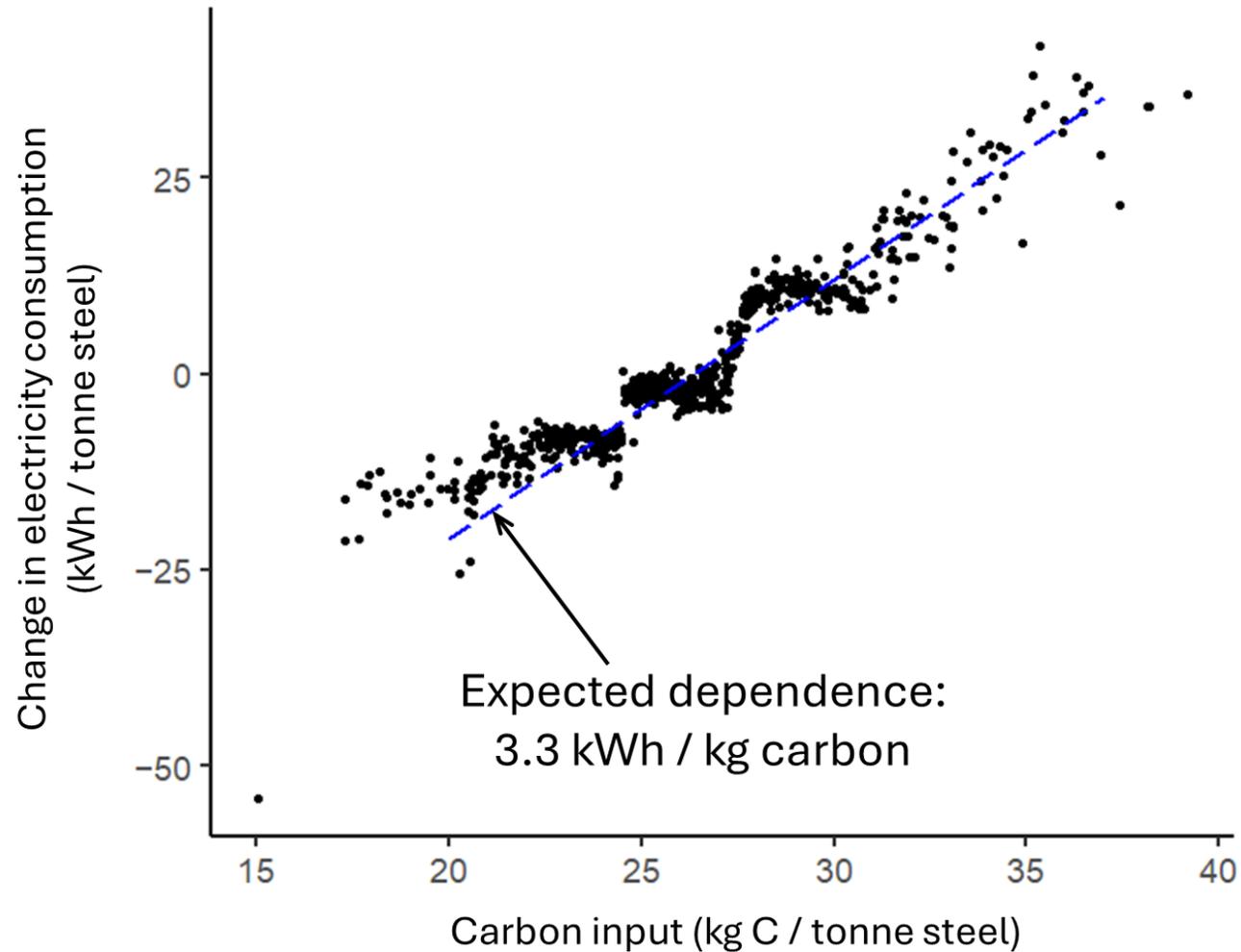
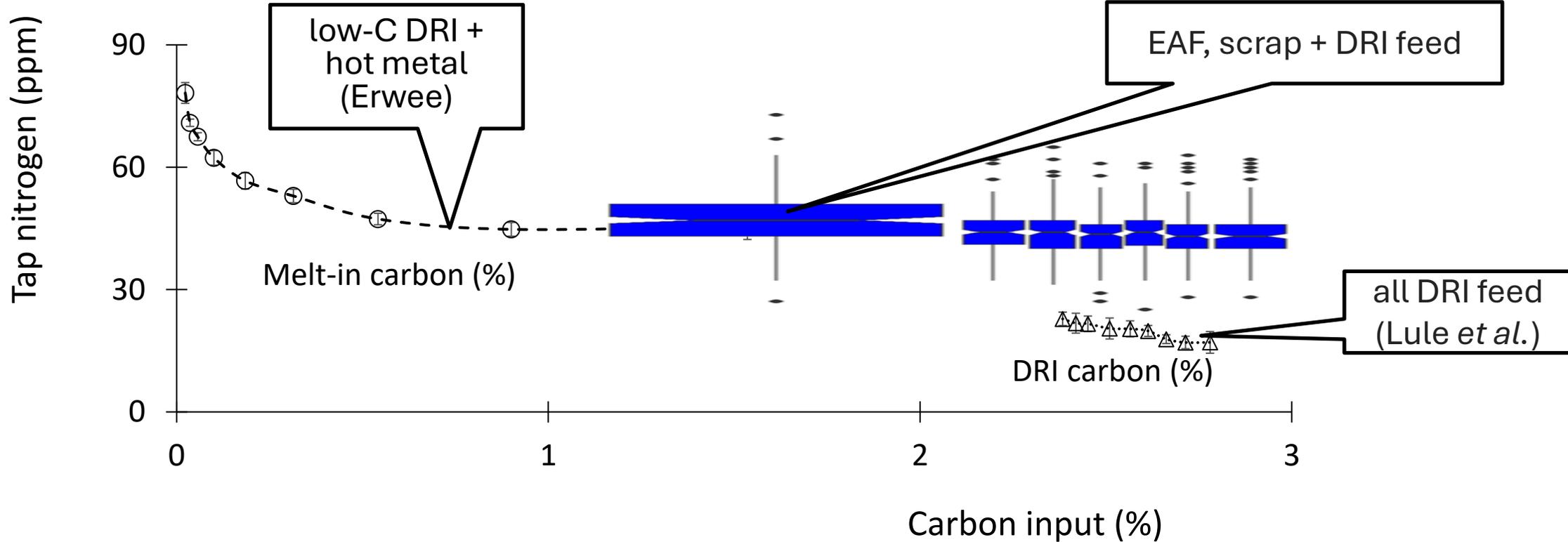Zhuo *et al.* (2024)
doi: 10.3390/met15010013.

Adding less carbon per heat
would save both electricity and lower Scope 1 CO_2 emissions

But wouldn't the corresponding decrease in lance oxygen increase electricity consumption?

For this operation:
Using more lance oxygen **increases** the electricity consumption, likely because of too-high FeO in slag (poorer foaming)

Theoretical dependence for oxidation of Fe
-5.3 kWh / Nm^3 O_2

Change in electricity consumption (kWh / tonne steel)

Oxygen input (Nm^3 O_2 / tonne steel)

Nitrogen removal in EAF: how much carbon do we really need?

Erwee & Pistorius: *Ironmaking & Steelmaking* **39,** 336–341 (2012).
Lule *et al.*: *AISTech 2009 Proceedings* **I,** 489–498 (2009).
Pistorius, ICS2025

Summary: effects of DRI chemistry on EAF largely well-understood:

- Increased gangue (larger slag volume):
  Increased electricity consumption & lower yield;
  possible increased refractory wear

- Higher carbon:
  Increased electricity consumption *for given oxygen input*;
  nitrogen in steel at tap not necessarily lower

- Higher phosphorus:
  Higher [%P]$_{steel}$; dephosphorization reaction does not reach equilibrium

Acknowledgements

- Students / alumni and researchers whose results are included in this presentation: Grant Kenny; Quantum Zhuo; Rafaela Rapalo; Shengqiang Song