The role of slags and other by-products within circular economy in the steel industry

› Carbon footprint calculation for slag from a reducing electric furnace

› Dr. Julian Suer (tkSE | CCM/SSP/Alternative Technologies)

5.–6. MARCH 2025
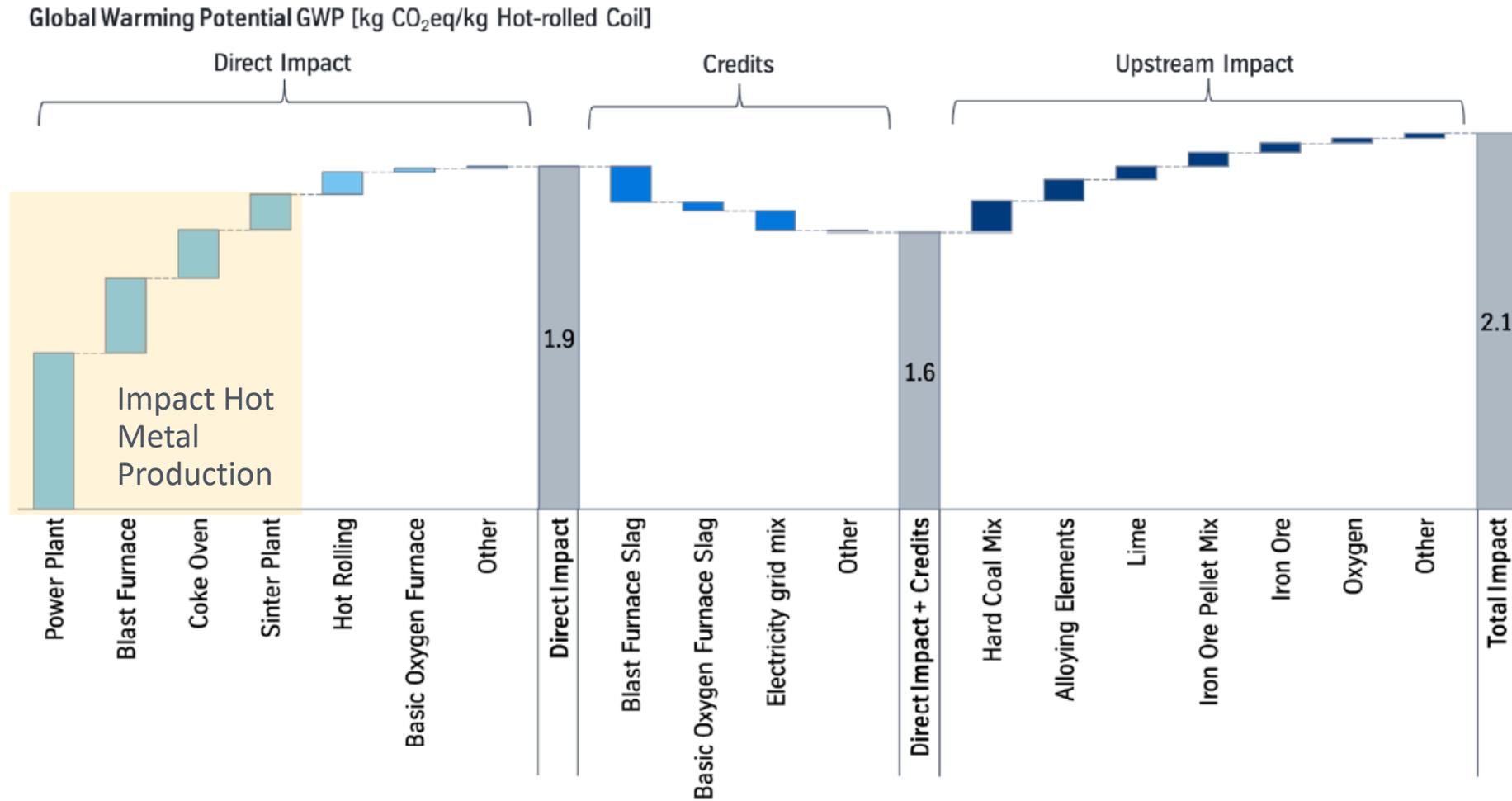
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FEhs

Transformation of the steel industry
Base Case
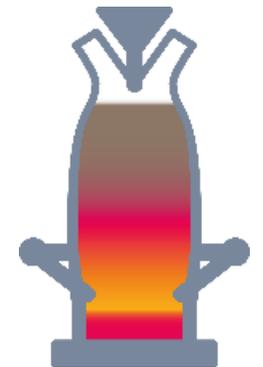
Global Warming Potential GWP [kg CO_2eq/kg Hot-rolled Coil]

Blast Furnace Route

Direct Impact — Power Plant, Blast Furnace, Coke Oven, Sinter Plant, Hot Rolling, Basic Oxygen Furnace, Other, Direct Impact: 1.9

Impact Hot Metal Production

Credits — Blast Furnace Slag, Basic Oxygen Furnace Slag, Electricity grid mix, Other, Direct Impact + Credits: 1.6

Upstream Impact — Hard Coal Mix, Alloying Elements, Lime, Iron Ore Pellet Mix, Iron Ore, Oxygen, Other, Total Impact: 2.1
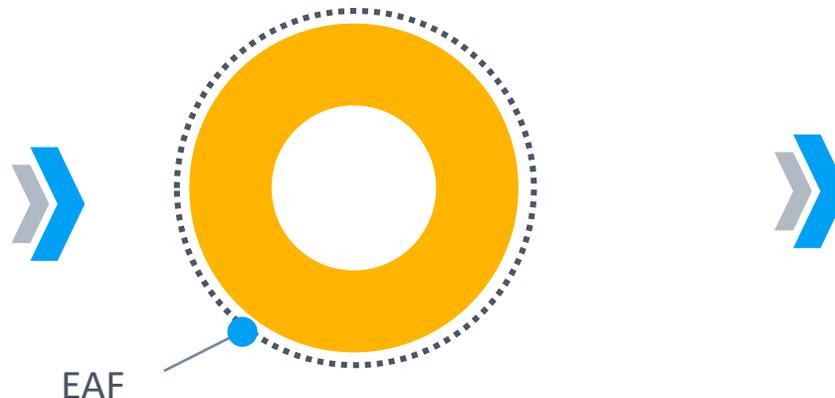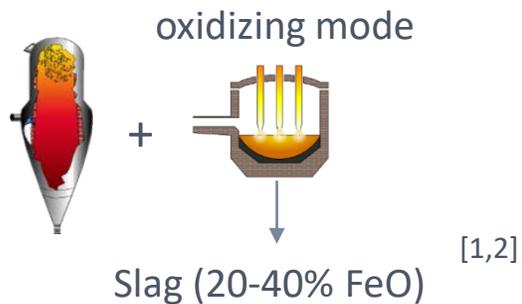
Suer, J.; Ahrenhold, F.; Traverso, M.: Carbon Footprint and Energy Transformation Analysis of Steel Produced via a Direct Reduction Plant with an Integrated Electric Melting Unit. Journal of Sustainable Metallurgy (2022). DOI:10.1007/s40831-022-00585-x
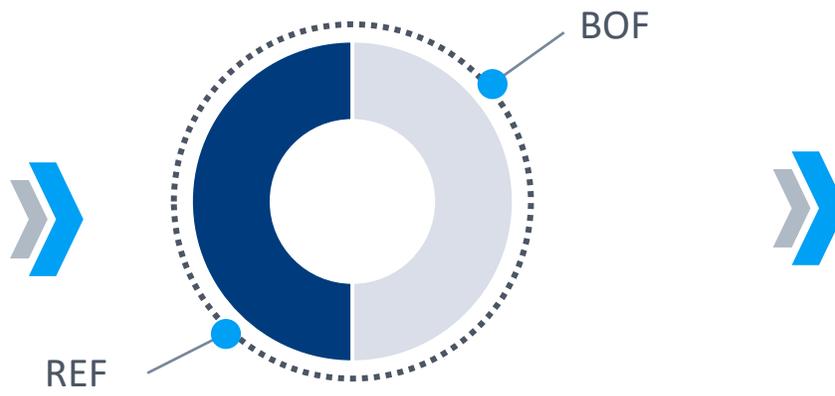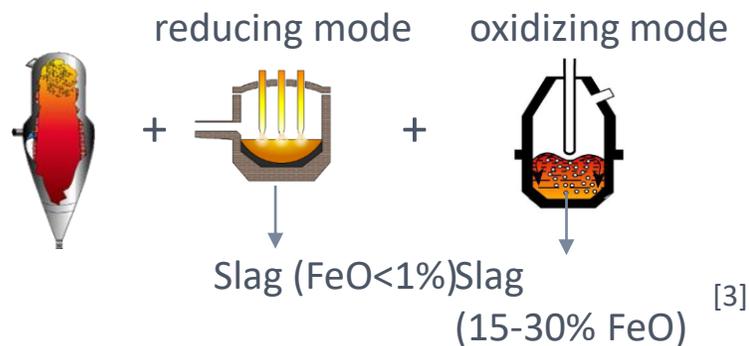
Low emission steel production routes
Impact on slag production

DRI-EAF – Route

oxidizing mode

+

Slag (20-40% FeO) [1,2]

EAF

Single slag work leads to low valuable slag

DR-REF-BOF – Route

reducing mode   oxidizing mode

+   +

Slag (FeO<1%) Slag (15-30% FeO) [3]

BOF

REF

Extra effort of dividing slag work on two processes allows to produce high-valuable slag in REF

Shared slag work allows to produce cement clinker substitute in REF

[1] Stagnoli, P. (2020). Decarbonising the steelmaking process. Steel Times International, 44(5), 24-27.
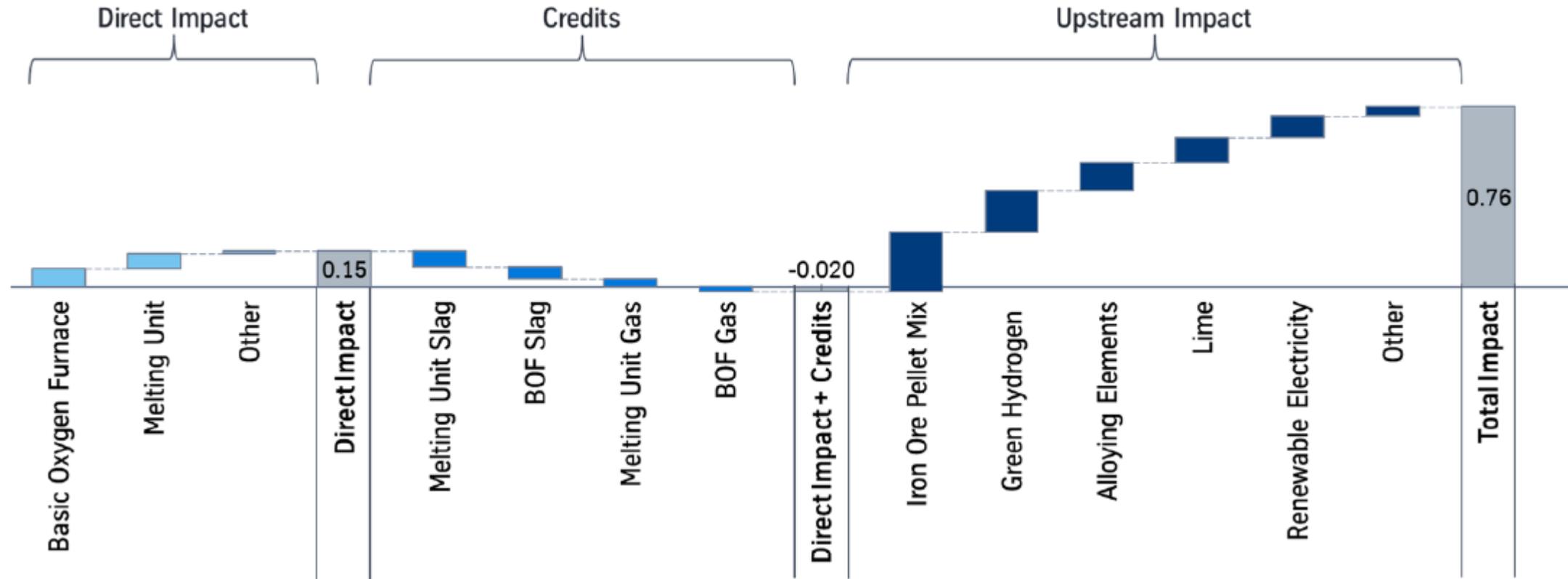[2] Lüngen, I. H. B., & Schmöle, P. (2022). Wege zu einer klimaneutralen Stahlerzeugung.
[3] Zago, Vernilli, Cascudo (2023): The reuse of basic oxygen furnace slag as concrete aggregate to achieve sustainable development: characteristics and limitations
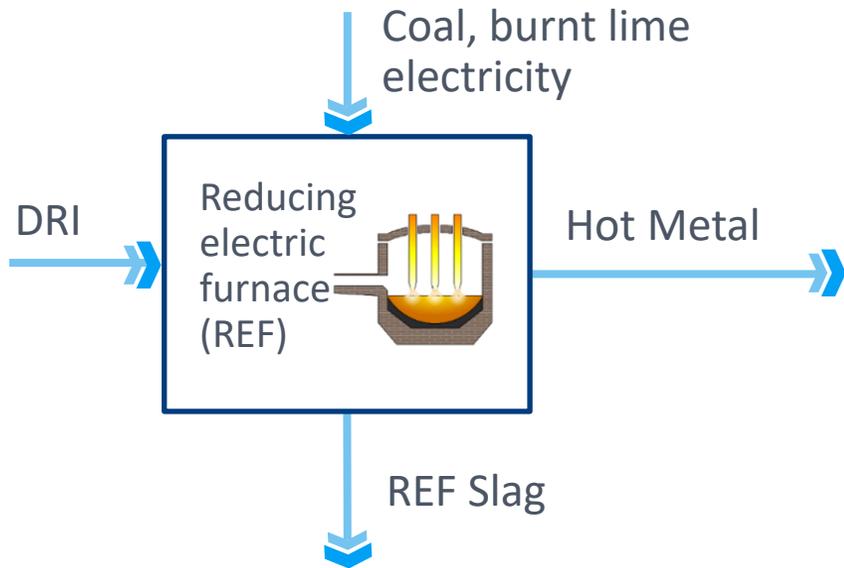
Transformation of the steel industry
Hydrogen based DR + REF + BOF - Route

Global Warming Potential GWP [kg CO₂eq/kg Hot-rolled Coil]

Direct Impact — Credits — Upstream Impact

0.15 · -0.020 · 0.76

Basic Oxygen Furnace · Melting Unit · Other · Direct Impact · Melting Unit Slag · BOF Slag · Melting Unit Gas · BOF Gas · Direct Impact + Credits · Iron Ore Pellet Mix · Green Hydrogen · Alloying Elements · Lime · Renewable Electricity · Other · Total Impact

Suer, J.; Ahrenhold, F.; Traverso, M.: Carbon Footprint and Energy Transformation Analysis of Steel Produced via a Direct Reduction Plant with an Integrated Electric Melting Unit. Journal of Sustainable Metallurgy (2022). DOI:10.1007/s40831-022-00585-x

SAVE CO$_2$ – System Boundary

Coal, burnt lime electricity

DRI → Reducing electric furnace (REF) → Hot Metal

REF Slag

Slag Composition

$$B = \frac{CaO}{SiO_2} = 1.1$$

Element	Share [%]
SiO$_2$	36
CaO	40
Al$_2$O$_3$	17
FeO	0,3
MgO	5

Trials Series 2, July 2024

SAVE CO$_2$ – System Boundary
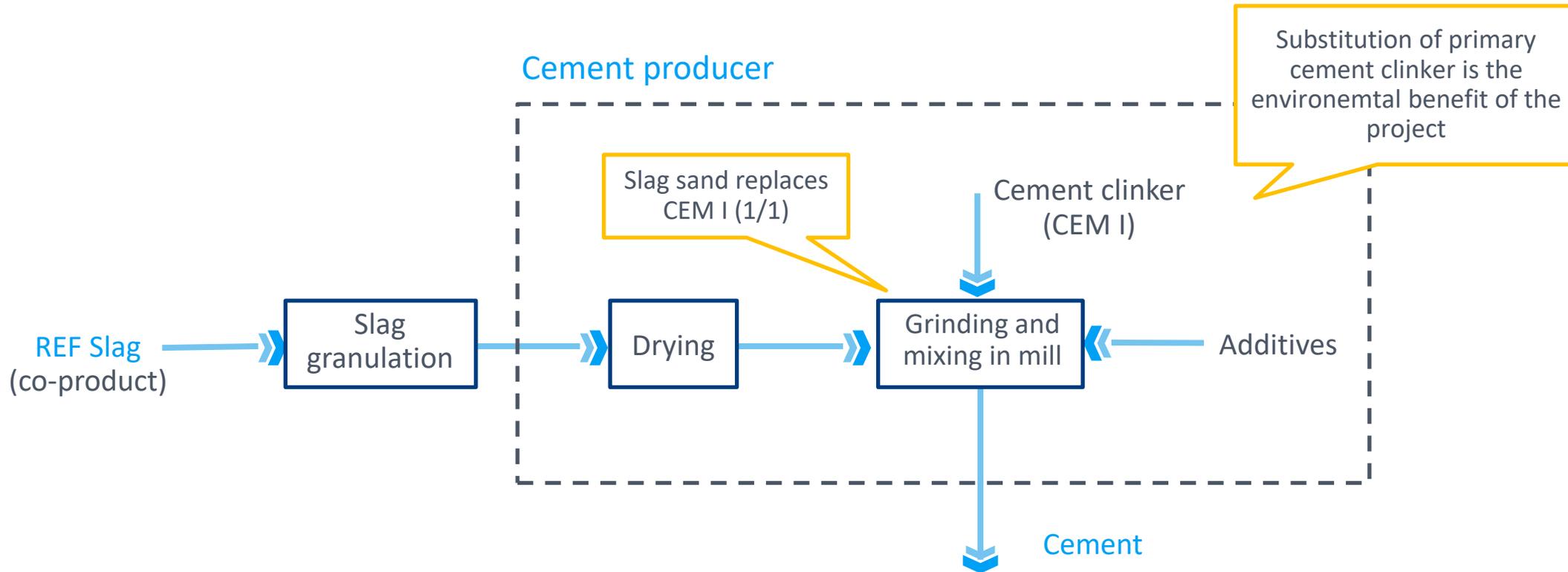
1 kg granulated REF slag substitutes 1 kg cement clinker (CEM I)

Cement Clinker Substitute

GWP [kg CO_2e/kg CEM I] [1]

0.84

- REF slag substitutes CEM I 1/1

- Primary cement clinker has a carbon footprint of 0.84 kg CO_2e/kg CEM I[1]

- How is the benefit shared between steel and cement producer within the blast furance route ?

[1] According to Sphera database „RER: CEM I 42.5 (burden free binders)"

Evaluation of blast furnace slag in ISO norms

LCA and EPDs for blast furnace slag

ISO 14044 (LCA)

Step 1:
Allocation should be avoided

- System partitioning ⊗
  Separating the burden for the hot metal and for the slag production; not practical for blast furnace operation because of highly integrated processes

- System expansion ✓
  Expanding the product system to include additional functions related to the co-product (Credit methodology)

Step 2:

Apply allocation ⊗

| System expansion: |
| Slag value 0.84 kg CO_{2eq}/kg [2] |

EN 15804 (EPD)

Step 1:
Allocation should be avoided

- System partitioning ⊗

Step 2:

Apply allocation:
Apply economic allocation ✓

Step 3:
If the difference in income generated by the products is small;[1] the allocation must be based on physical characteristics (mass, volume) ⊗

Area of conflict

| Economic allocation: |
| Slag value 0.1 kg CO_{2eq}/kg [3] |

Slag evaluation depends on considered regulatory

1: Contributions to income in the order of 1% or less are considered very low. A difference in company income of more than 25 % is considered large
2: Evaluation according to CEM I according to World Steel.
3: LESS Rulebook: 20240422_Annex_LESS-Rulebook.pdf

SAVE CO_2 Project | Carbon footprint calculation for slag from a reducing electric furnace | Dr. Julian Suer | tkSE (CCM/SSP/Alternative Technologies) | 06.03.2025

Evaluation of blast furnace slag in ISO norms
LCA and EPDs for blast furnace slag

ISO 14044 (LCA)

Step 1:
Allocation should be avoided

- **System partitioning**
Separating the burden for the hot metal and for the slag production; not practical for blast furnace operation because of highly integrated processes

- **System expansion**
Expanding the product system to include additional functions related to the co-product (Credit methodology)

Step 2:

Apply allocation

EN 15804 (EPD)

Step 1:
Allocation should be avoided

- **System partitioning**

Step 2:

Apply allocation:
Apply economic allocation

Step 3:
If the difference in income generated by the products is small;[1] the allocation must be based on physical characteristics (mass, volume)

> Might be possible for slag from a reducing electric furnace

| System expansion: |
| Slag value 0.84 kg CO_{2eq}/kg [2] |

Area of conflict

| Economic allocation: |
| Slag value 0.1 kg CO_{2eq}/kg [3] |

Slag evaluation depends on considered regulatory

1: Contributions to income in the order of 1% or less are considered very low. A difference in company income of more than 25 % is considered large
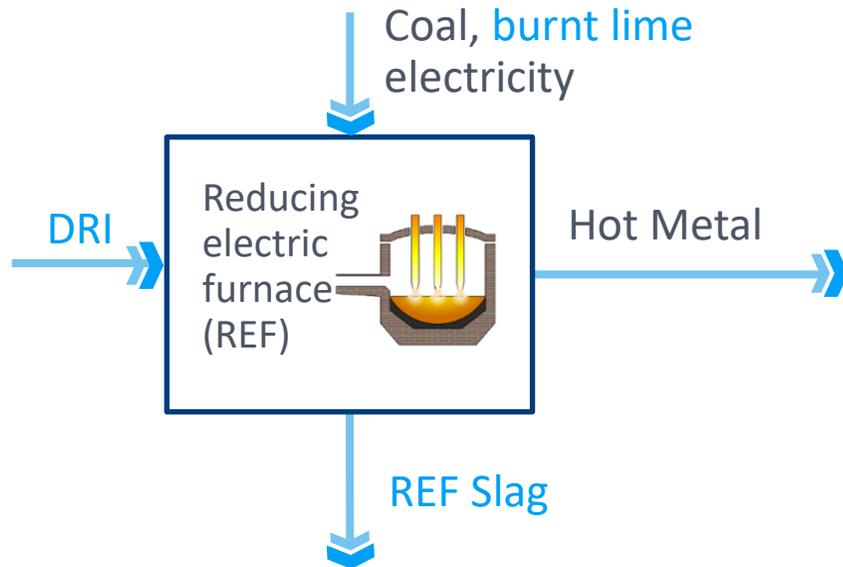2: Evaluation according to CEM I according to World Steel.
3: LESS Rulebook: 20240422_Annex_LESS-Rulebook.pdf

System partitioning for reducing electric furnace
What is the burden for producing the highly reactive slag ?

Coal, burnt lime
electricity

DRI → Reducing electric furnace (REF) → Hot Metal

REF Slag

Using burnt lime for:

- Viscosity
- Desulfurization

} required for process, anyway

- Slag properties (reactivity) – extra burden for cement producer

Which is the amount of extra burnt lime for the slag reactivity?

A part of the used burnt lime is used for generating a highly reactive slag

Use of additional burnt lime for slag reactivity

$$\Delta = 0.14 \frac{kg\ burnt\ lime}{kg\ Slag} 1.2 \frac{kg\ CO_2e}{kg\ burnt\ lime}$$

$$B = \frac{CaO}{SiO_2}$$

$$B_{Trials} = 1.1$$

$$SiO_2 = 36\%$$

$$CaO = 40\%$$

$$B_{min} = 0.75^{[1]}$$

$$SiO_2 = 40\%$$

$$CaO = 30\%$$

Difference is used for slag optimaztion

➡ $$0.27\ kg/kg\ slag < CaO < 0.40\ kg/kg\ slag^{[3]}$$

➡ $$\Delta = 0.14\ \frac{kg\ burnt\ lime}{kg\ Slag}^{[2]} \times 1.2\ \frac{kg\ CO_2e}{kg\ burnt\ lime} = 0.17\ \frac{kg\ CO_2e}{kg\ Slag}$$

[1] Elmomen (2017): Influence of Slag Composition and Temperature on Silicon Distribution between Slag and Hot Metal in the Egyptian Blast Furnace No.III
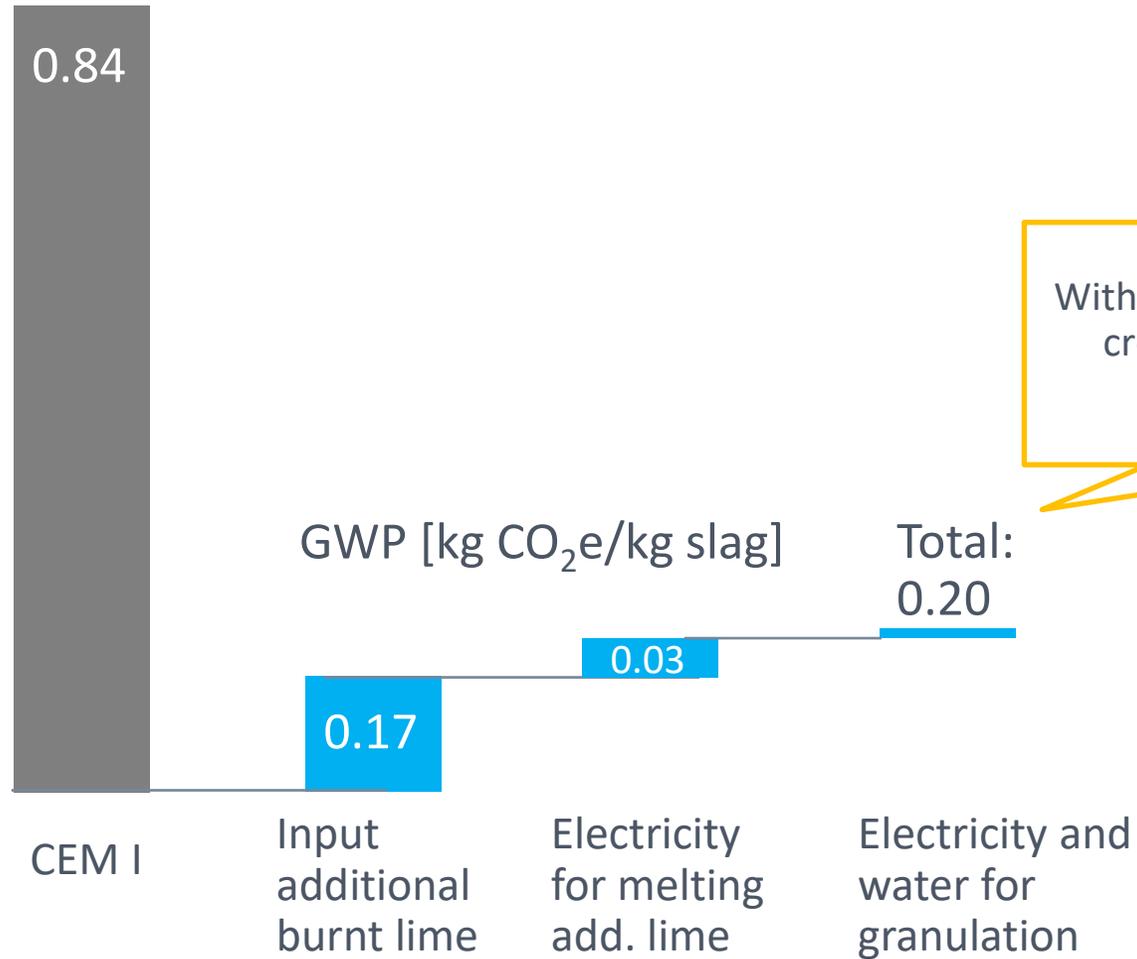[2] Assumption. 95% CaO in burnt lime
[3] Dilution effects need to be considered

Benefit and burden of CEM I substitution

GWP [kg CO_2e/kg CEM I]

0.84

With a burden of 0.20 kg CO_2e/kg slag a cross-industriell benefit of 0.84 kg CO_2e/kg can be achieved

GWP [kg CO_2e/kg slag]

Total: 0.20

0.03

0.17

CEM I

Input additional burnt lime

Electricity for melting add. lime

Electricity and water for granulation

System partitioning might be possible for slag production in REF process
Simplified example for calculation of system division

- System partitioning in LCA and epds first choice
- In blast furnace route it is not practical to separate the burden for hot metal and slag production
- For a reducing electric furnace (REF) a possible methodology was presented.

> System partitioning reflects the real environmental burden

Burden for hot metal production →

Extra burden for slag production →

Reducing electric furnace (REF)

→ Hot metal

→ REF slag
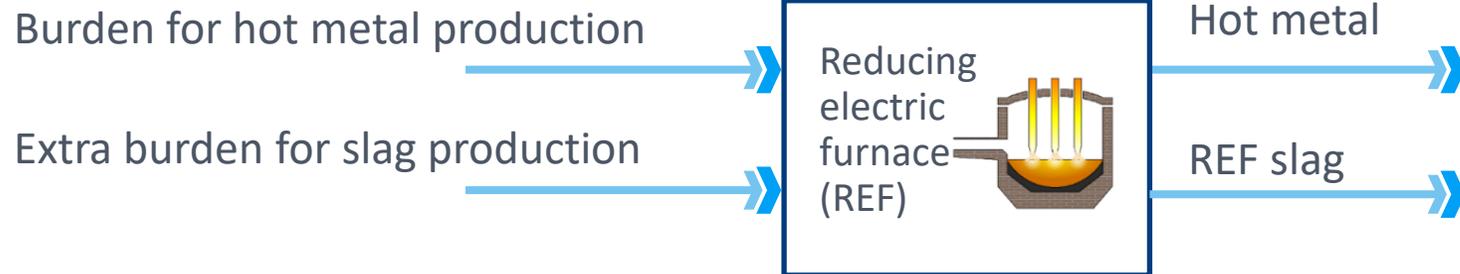
Partitioning approach:
Here only the extra lime for reactive slag is considered as burden

Slag Value:

➤ Use of extra burnt lime for reactivity
➤ Melting of extra burnt lime

0.20 kg CO$_2$e/kg slag
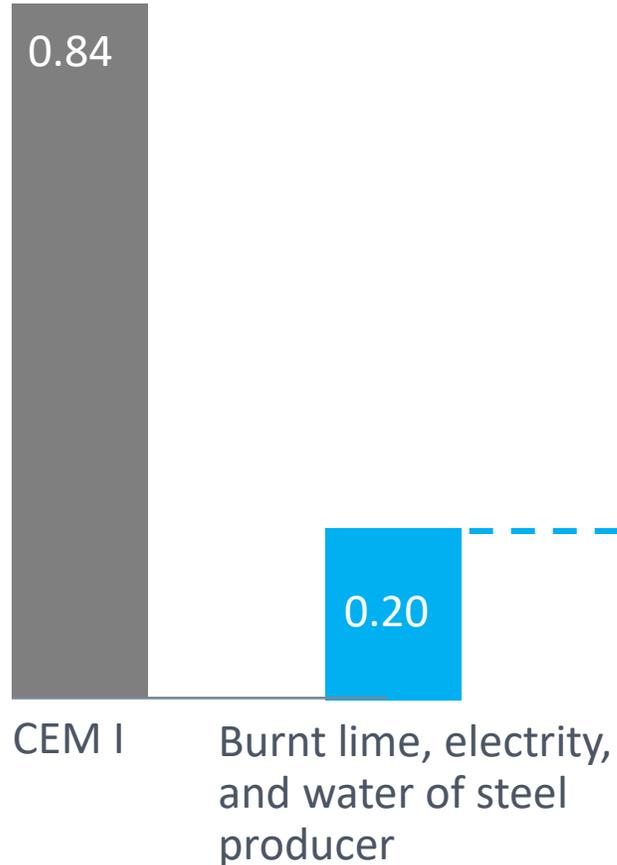
Detailed engineering required:

- Effects in REF are more complex than highlighted here.
- CaO content has impact on electrical conductivity; melting point etc in dependency of chemical composition needs to be evaluated
- Minimum input of burnt lime could be different from BF route because of different tapping temperatures

➤ More detailed caluclation and primary data are necessary for system partitioning
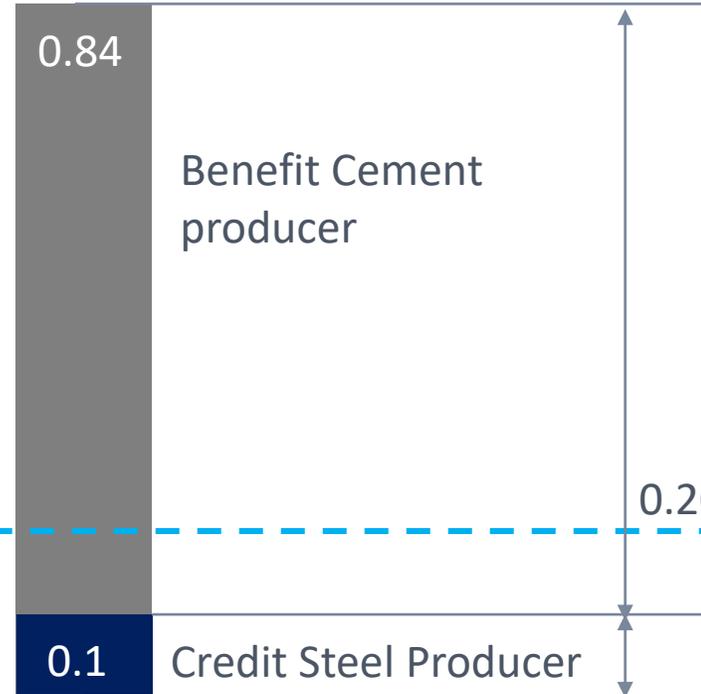
Economical allocation of slag has risk of not incentivizing steel maker

GWP [kg CO_2e/kg granulated Slag]

0.84

0.20

CEM I

Burnt lime, electricity, and water of steel producer

Economical Allocation

0.84

Benefit Cement producer

0.20

0.1 Credit Steel Producer

Total Benefit of CEM I substitution

Burden Steel Producer

0.1 kg CO_2e/kg: according to LESS aproach, based on economic allocation [1]

The environmental burden of steel producer needs to be considered for giving incentive

[1] LESS Rulebook: 20240422_Annex_LESS-Rulebook.pdf

- Extra effort of dividing slag work on two processes allows to produce a high valuable slag in reducing electric furnace (REF)

- Evaluation of blast furnace slag via system partitioning was not practical so far

- An example of system partitioning for the slag from the REF is presented but needs further evaluation

- 0.20 kg CO_2e/kg slag is the burden of the steel producer for the input of additional burnt lime and electricity

- With this burden a cross-industriell benefit of 0.84 kg CO_2e/kg slag can be achieved.

Thank you for your attention

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Different slag compositions

Tab. 2.5-2: Chemische Zusammensetzung von Hochofenschlacke (HO-Schl.) in M % [JUCKES, 1995].

Inhaltsstoffe	HO-Schl. in M %
SiO_2	33-40
Al_2O_3	8-14
CaO	31-42
MgO	7-15
Fe_{gesamt}	0,2-0,7
Mn_{gesamt}	0,2-0,8
P_2O_5	<0,05
Na_2O	0,3-1,2
K_2O	0,6-1,2
S_{gesamt}	0,7-1,6
TiO_2	0,1-2,7
CaO/SiO_2	0,8-1,2
$(CaO+MgO)/SiO_2$	1,0-1,3