

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

- **Circular valorization of steelmaking by-products: the Italian case study in the HEPHAESTUS project**
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HEPHAESTUS PROJECT

Heavy and Extractive industry wastes PHAsing out through ESG Tailings Upcycling Synergy

HORIZON-CL4-2021-TWIN-TRANSITION-01-20

Project number 101058696



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Steel is essential in daily life, but its production generates significant waste, particularly slag, dust, and sludge

80% of steelmaking waste consists of by-products like EAF dust, containing valuable metals (Fe, Zn, Ni, Cr) but also hazardous elements (Pb, Cd)

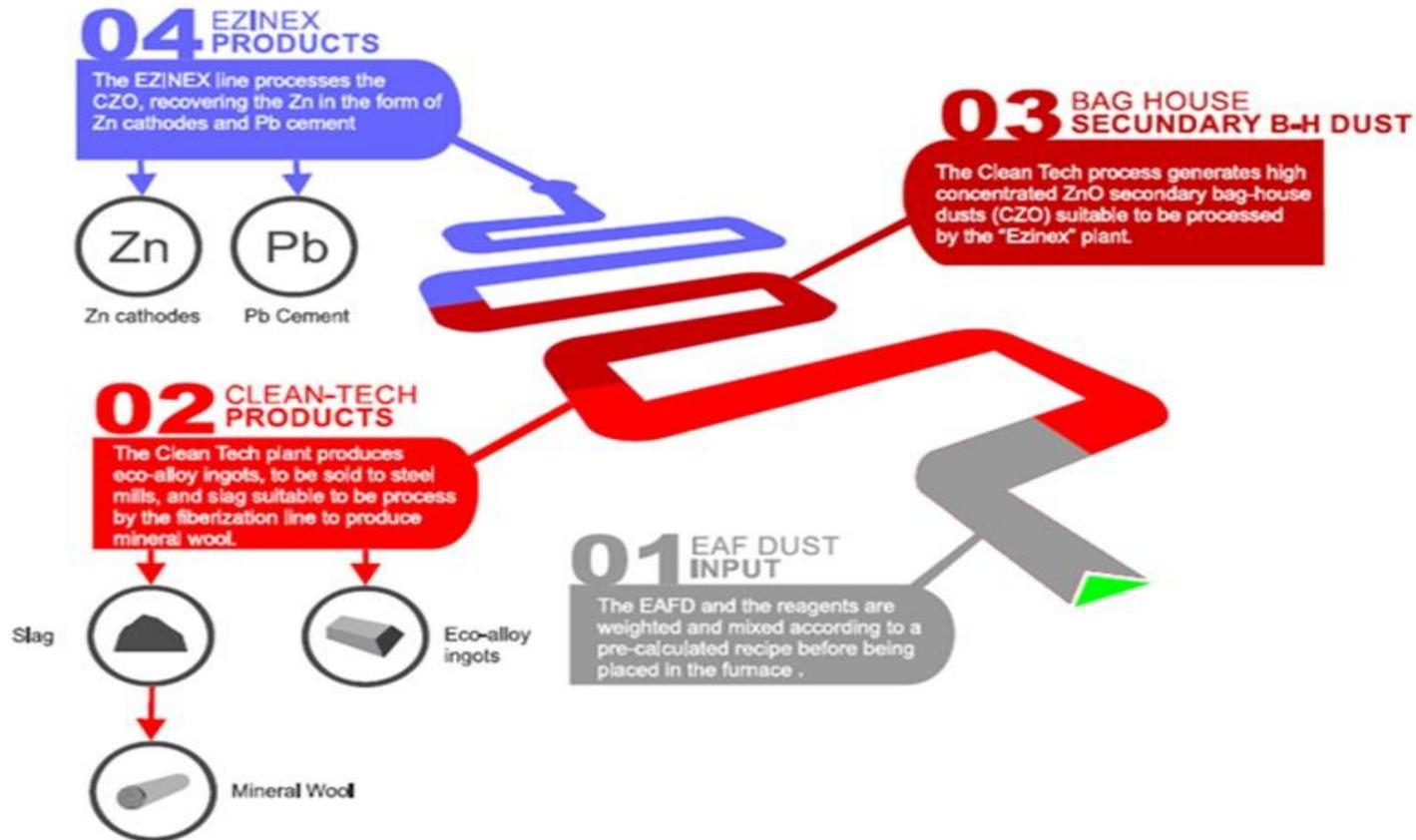
Recycling these residues is the key to reduce landfill waste

HEPHAESTUS project aims to transform these by-products into high-value materials, reintegrating them into the production cycle

This allow to minimize environmental impact, disposal costs and to implement a circular economy model

INTEGRATED APPROACH

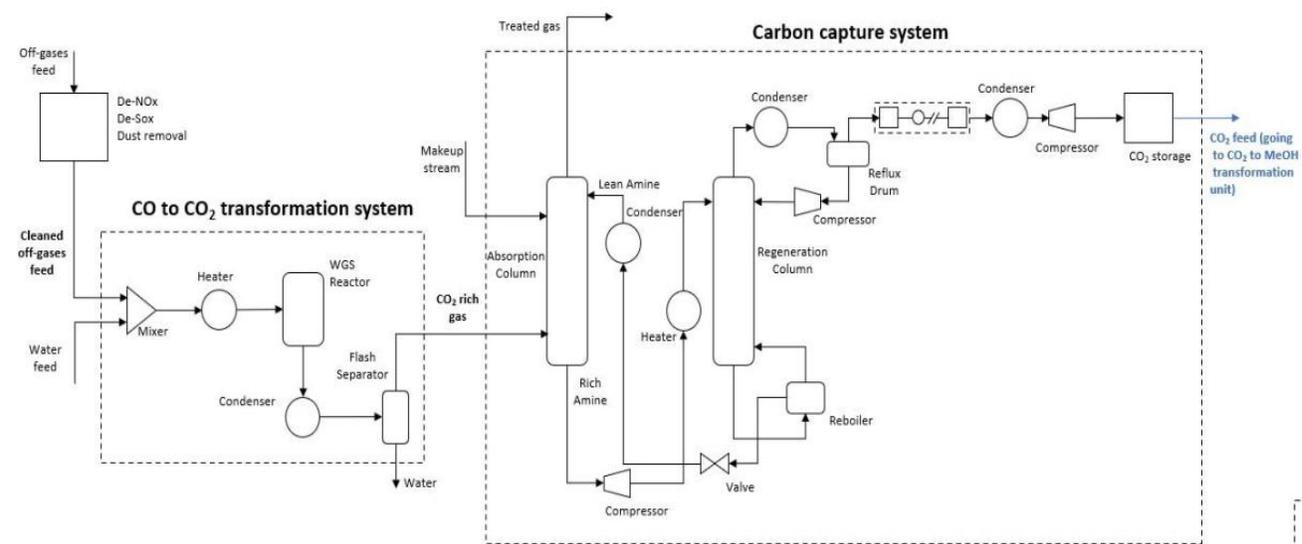
HEPHAESTUS project faces this challenge by integrating three key operations:



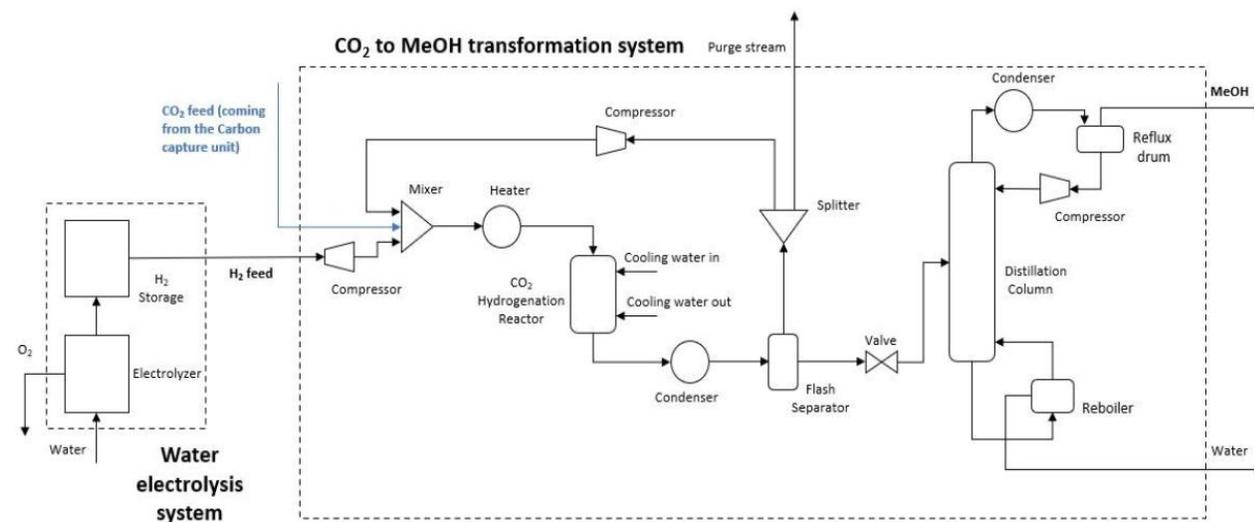
- 1 **CleanTech Electric Furnace** – Carbothermic reduction for EAF dust and oxidized residues
- 2 **Fibre Drawing Unit** – Direct spinning of molten slag into mineral wool
- 3 **EZINEX Process** – Electrolytic recovery of 99.99% pure zinc

INTEGRATED APPROACH

Additionally, a feasibility study on a **CCT unit** suggests the possibility to capture CO_2 from the furnace and convert it into methanol, reinforcing circular economy principles



Block diagram of the CO to CO₂ transformation system and carbon capture system



Block diagram of the water electrolysis system and CO₂ to MeOH transformation system

INPUT MATERIALS

The project will process **various waste materials**:

✓ **Mining waste dust**, generated from ore extraction and refining processes. Contain **residual metals (Fe, Al, Ti, Si)** that can be recovered

✓ **EAF and AOD dust**, by-products generated by **steel refining** processes, classified as **special waste** due to their **pyrophoric and unstable nature**. Contain **high-value metals** such as **iron (Fe), chromium (Cr), nickel (Ni), and zinc (Zn)**. In some countries, **EAF dust landfilling is banned**, making recycling a crucial challenge

✓ **Bauxite residue (red mud) from the Bayer process**, a by-product of aluminum production, with a fine particle size (0.49µm) and high alkalinity, making disposal difficult. Contains iron oxides (Fe₂O₃), silica (SiO₂), and titanium dioxide (TiO₂). Classified as non-hazardous, but large-scale accumulation presents environmental challenges

	Bauxite residues	EAF		AOD	
		Austenitic steel	Ferritic steel	Austenitic steel	Ferritic steel
SiO ₂	5,73	6,70	6,84	4,91	4,07
Al ₂ O ₃	21,22	1,51	0,89	1,36	1,56
CaO	9,90	8,02	7,27	18,74	9,84
MgO	0,23	5,06	3,42	1,32	1,33
Fe _{TOT}	29,95	26,93	33,40	32,11	44,07
Cr ₂ O ₃		14,61	14,38	15,41	18,30
NiO		2,18	0,43	3,17	0,43
P ₂ O ₅		0,04	0,03	0,03	0,02
ZnO		11,21	12,62	4,11	4,90
MnO		4,69	3,00	4,60	2,12
MoO ₃		0,33	0,02	1,01	0,06
CuO		0,49	0,21	0,39	0,15
TiO ₂		0,30	0,37	0,06	0,07
V ₂ O ₅		0,11	0,13	0,05	0,07
Pb ₃ O ₄		0,46	0,21	0,25	0,11
ZrO ₂		0,21	0,21	0,21	0,21

Average composition of waste materials

CleanTech Electric Furnace

Objective. Recover valuable metals and optimize slag composition for fiberization

Technology. The 5MVA furnace works through carbothermic reduction of EAF dusts and steel residues, melting the feedstock at ~1600°C

The outputs are: **inert slag**, to be used for mineral wool production; **ferro-alloy**, recovered from metal bath; **dust enriched in ZnO**, collected and processed via EZINEX

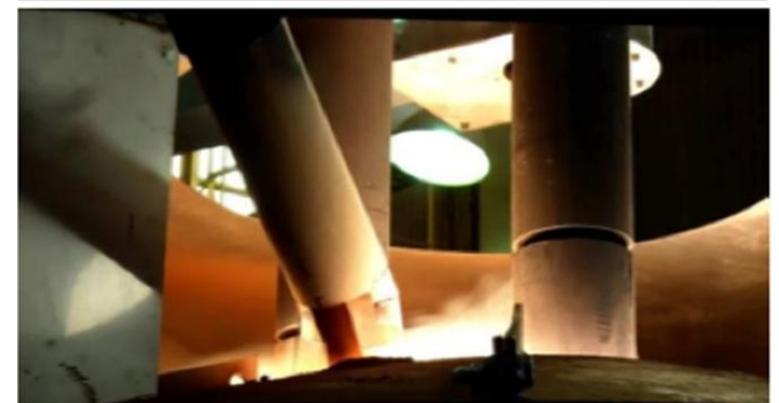
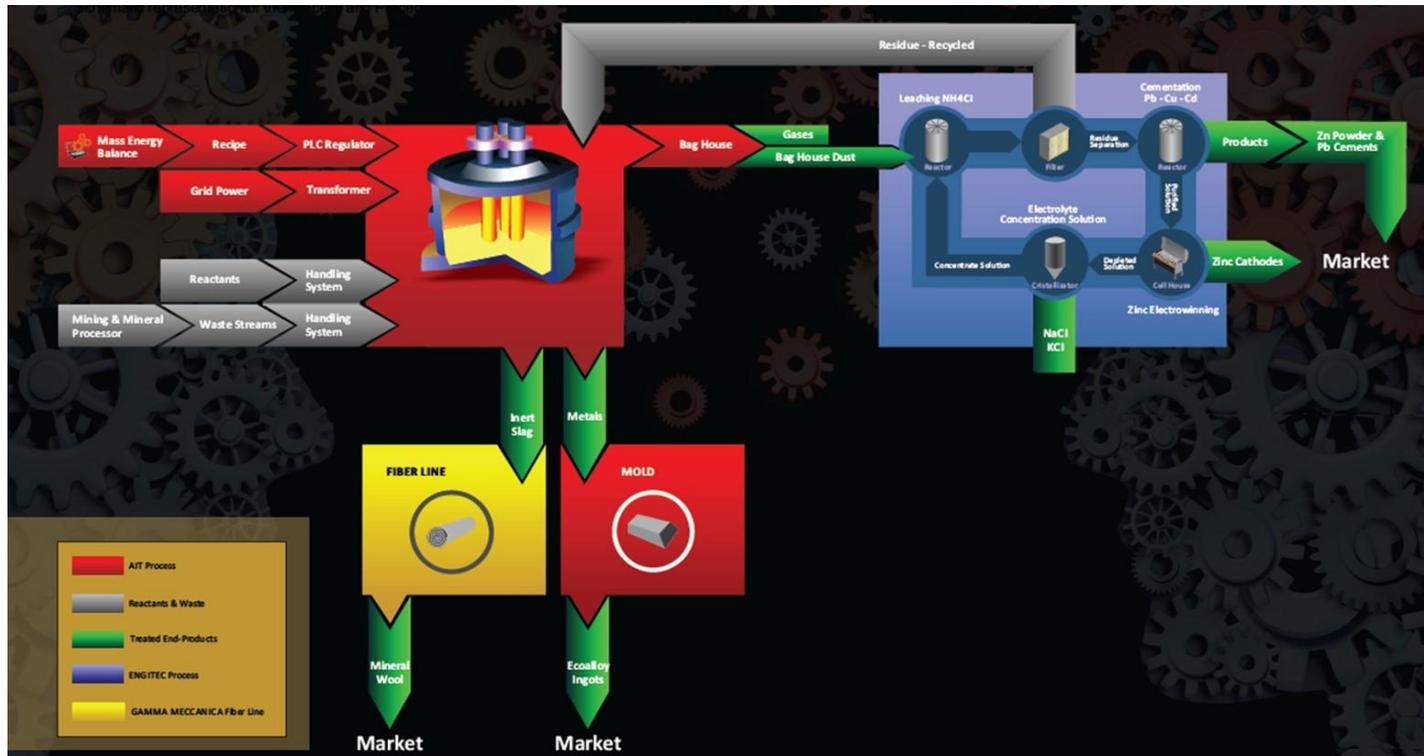
Index	Purpose	Optimal Range
Acidity Index (A)	Balances acidic and basic oxides for vitrification	1.8 - 2.1
Kz Index	Controls slag fluidity at processing temperature	0.64 – 0.75
KNB Index	Determines elasticity and fiber-forming ability	30 - 40
SHG Index	Predicts structural behavior of the slag matrix	1.3 - 1.4

In-furnace slag optimization. To produce slag suitable for mineral wool, composition is adjusted before tapping. Corrective additives (SiO_2 , Al_2O_3 , CaO , MgO , etc.) are introduced in precise amounts. Thermodynamic modeling (FactSage, Aspen Plus) predicts slag behavior. Key aspects are:

- ❖ Viscosity: 10-15 Poise at 1450-1500°C (ensuring fiberization)
- ❖ Acidity indices: A, Kz, KNB, SHG adjusted for vitrified structure formation

CleanTech Electric Furnace

The core of the CleanTech line is the reducing AC electrical furnace, thanks to a special charging system for the material into the furnace and a system for controlling the positioning of the electrodes on the surface of the melting bath, it is able to directly melt powdery inorganic materials without the need of preliminary treatment



Fiberization process

Objective. Convert CleanTech slag into high-performance thermal insulation (mineral wool). Conventional mineral wool requires virgin raw materials (basalt, dolomite). Steelmaking slag offers a sustainable alternative, reducing raw materials

Process Steps

1. Slag Preconditioning

Slag composition optimized for fiber formation (**silicate-rich** with balanced acidity)

Target composition: $\text{SiO}_2 > 40\%$, $\text{CaO} < 30\%$, $\text{Al}_2\text{O}_3 \sim 10\%$

2. Melting

Slag heated to **1450-1500°C** to achieve ideal viscosity

3. Fiber formation (centrifugation process)

Spinning disks stretch molten slag into fibers. Then rapid cooling **solidifies fibers**, preventing crystallization

4. Final processing

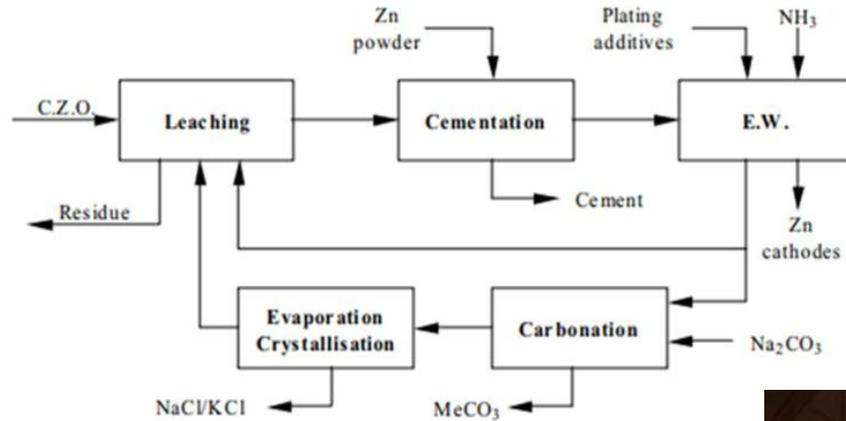
Fibers are sprayed with **organic binders** for cohesion

Cut, compressed, and packaged as **thermal insulation panels or rolls**



EZINEX process

Objective. Extract high-purity zinc (Zn) from steelmaking dust with an efficient hydrometallurgical process. Steel production generates Zn-rich dust (from galvanized scrap melting). Traditional Zn recovery is energy-intensive and requires pyrometallurgical steps. EZINEX provides a low-energy, selective Zn extraction process



Block diagram of the EZINEX process



Process Steps

1. Selective leaching

Steel dust is mixed with ammonium chloride to dissolve zinc. **Iron and other metals** remain undissolved. The outcome is a **zinc-rich solution**

2. Purification and precipitation

Zinc powder is added to the solution to remove metals like Pb, Cu. End result: a clean, zinc-rich solution

3. Electrolytic Zn recovery

The solution is fed into electrolysis cells, where **zinc** plate out on the cathodes. This step yields **high-purity zinc** (up to 99.99%)

Carbon Capture & Transformation (CCT)

Objective. Capture CO₂ from steel plant off-gas and convert it into methanol. CO is first converted into CO₂ to maximize CO₂ recovery. The Water Gas Shift reaction also generates H₂, needed for methanol synthesis. The CO₂ is then captured and purified, making the process more efficient.

Process steps

1. CO to CO₂ conversion from off-gas (WGS reaction)

Converts carbon monoxide into CO₂

Produces additional hydrogen for methanol synthesis

2. CO₂ capture and purification (Amine scrubbing with MDEA 40%)

Absorption column: CO₂ selectively captured by amine solution

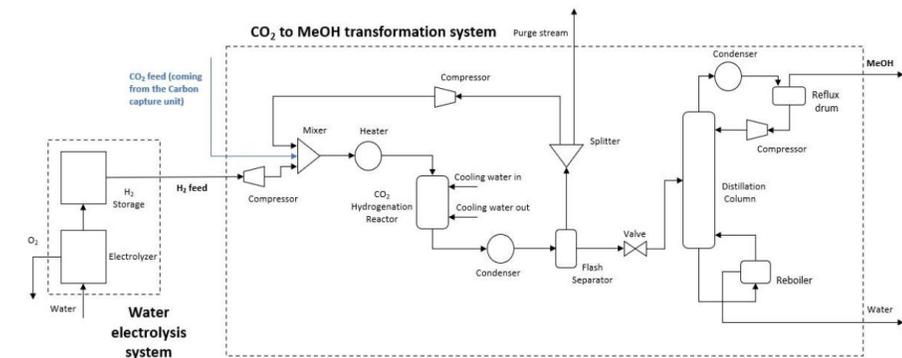
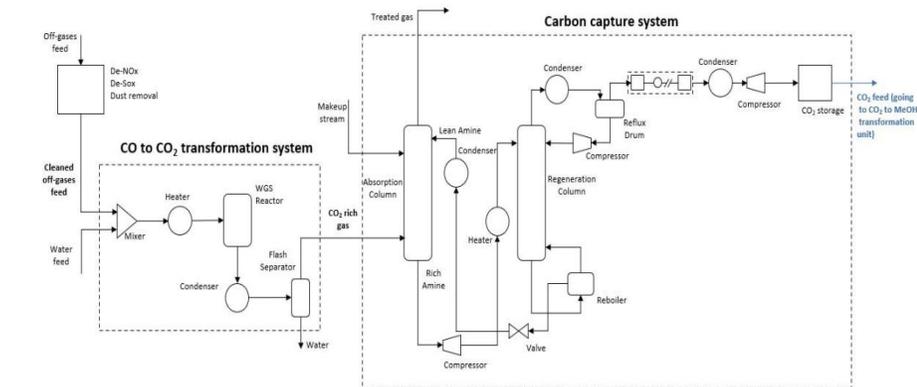
Regeneration column: CO₂ released and purified for further use

Compression & Storage: CO₂ is compressed and sent to methanol synthesis

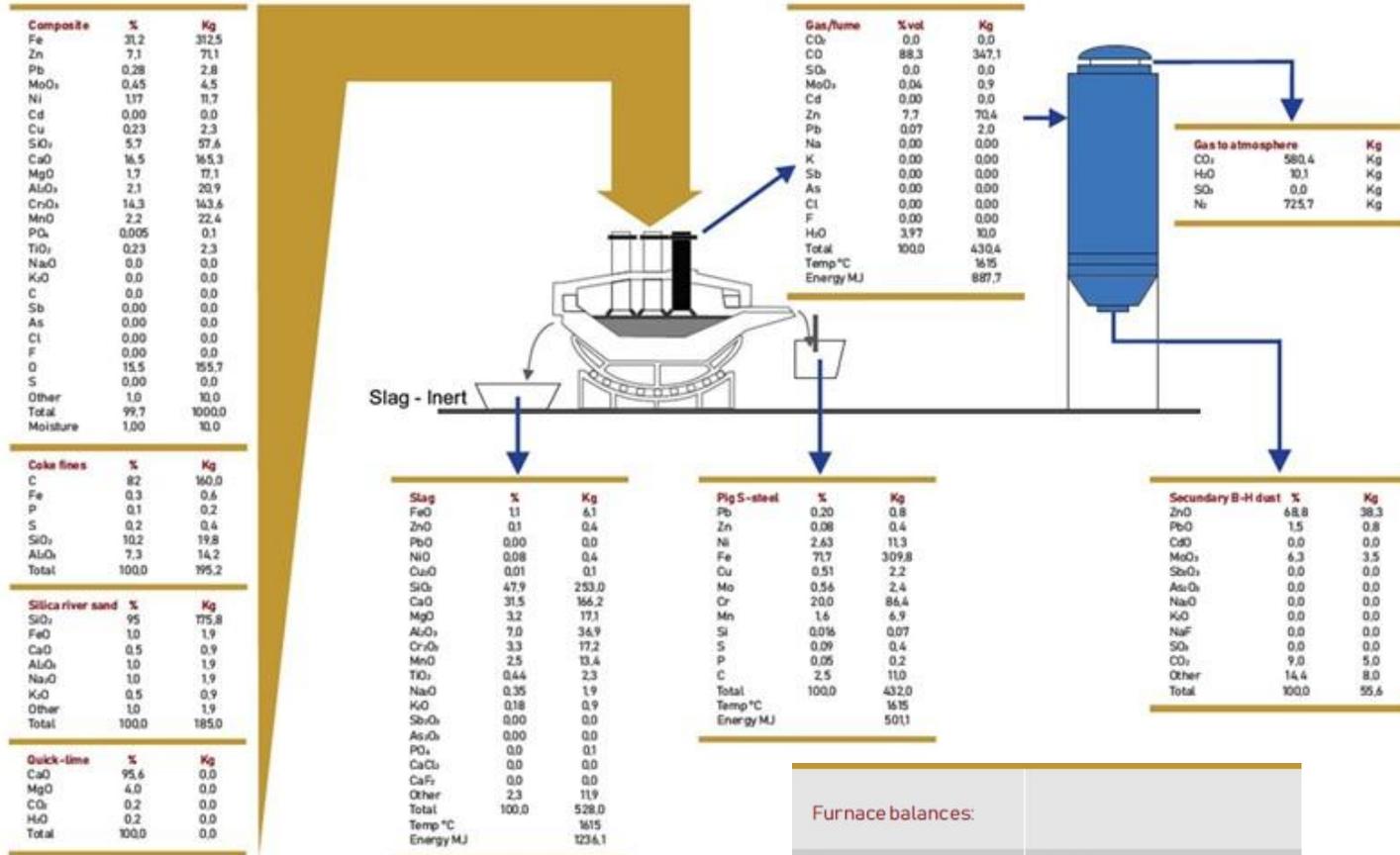
3. PEM electrolysis unit (green hydrogen production)

4. Methanol synthesis

Methanol is produced via catalytic hydrogenation in a multi-tubular fixed-bed reactor with Cu/ZnO/Al₂O₃ catalyst



Preliminary mass and energy balance



The image shows the preliminary mass and energy balance of the CleanTech furnace, obtained for an average dust composition from AOD austenitic steel production

Mass and energy balance has been used to calculate:

- ✓ carbon needed for oxide reduction
- ✓ best composition of charged materials to obtain products with appropriate composition (metal bath and inert slag)
- ✓ energy demand of the process

Furnace balances:	
Total materials in:	1390.2 Kg
Total materials out:	1390.4 Kg
Energy in products:	2624.9 MJ
Heats of reaction:	2353.8 MJ
Total energy in:	4978.8 MJ
@ furnace efficiency:	6383.0 MJ
Electrical power in:	1773.1 kWh/t Dust composite

Key sustainability and efficiency gains

1. ~90% input material reuse

Ferroalloy: ~30–40% of input dust (recovering Fe, Cr, Ni)

Zn-Rich Dust: ~20–25% (processed via EZINEX for high-purity zinc)

Slag: ~35–45% (converted into mineral wool)

Only residual wastes (e.g., small fraction of oxides) end up in landfill

2. 1–1.5 t CO₂ eq avoided per ton of EAF Dust

Less virgin extraction: recovering metals (Zn, Fe) on-site cuts emissions from mining & refining

No landfill: conventional disposal leads to extra CO₂ from transport and secondary processing

Lower carbon footprint relative to other traditional disposal/recovery routes

3. Up to 20% net energy reduction with heat recovery

Off-gas utilization: capturing and reusing high-temperature furnace gases

Efficient carbothermic reactions: minimizing extra fuel needed

Lower operating costs: less electricity required overall

Next steps – HEPHAESTUS implementation

1 Pilot plant construction

Installation of key process units (CleanTech Furnace, EZINEX, Fiberization)
Start-up and testing phase in **Italy and Greece**

2 Process optimization & validation

Fine-tuning mass & energy balance
Performance assessment for material recovery (Zn, Fe, slag)

3 Scaling up & industrial replication

Evaluation of large-scale feasibility
Collaboration with industry partners for wider implementation

4 Environmental & economic assessment

Full LCA (Life Cycle Assessment) to quantify impact
Cost-benefit analysis to ensure long-term sustainability



HEPHAESTUS

THANK YOU!

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