

# CircSmeltSteel



## CircSmeltSteel

Integration of Complex Metallurgical By-Products in Electric Smelting Furnace  
Operation: Process Strategy and Target Outcomes within CircSmeltSteel

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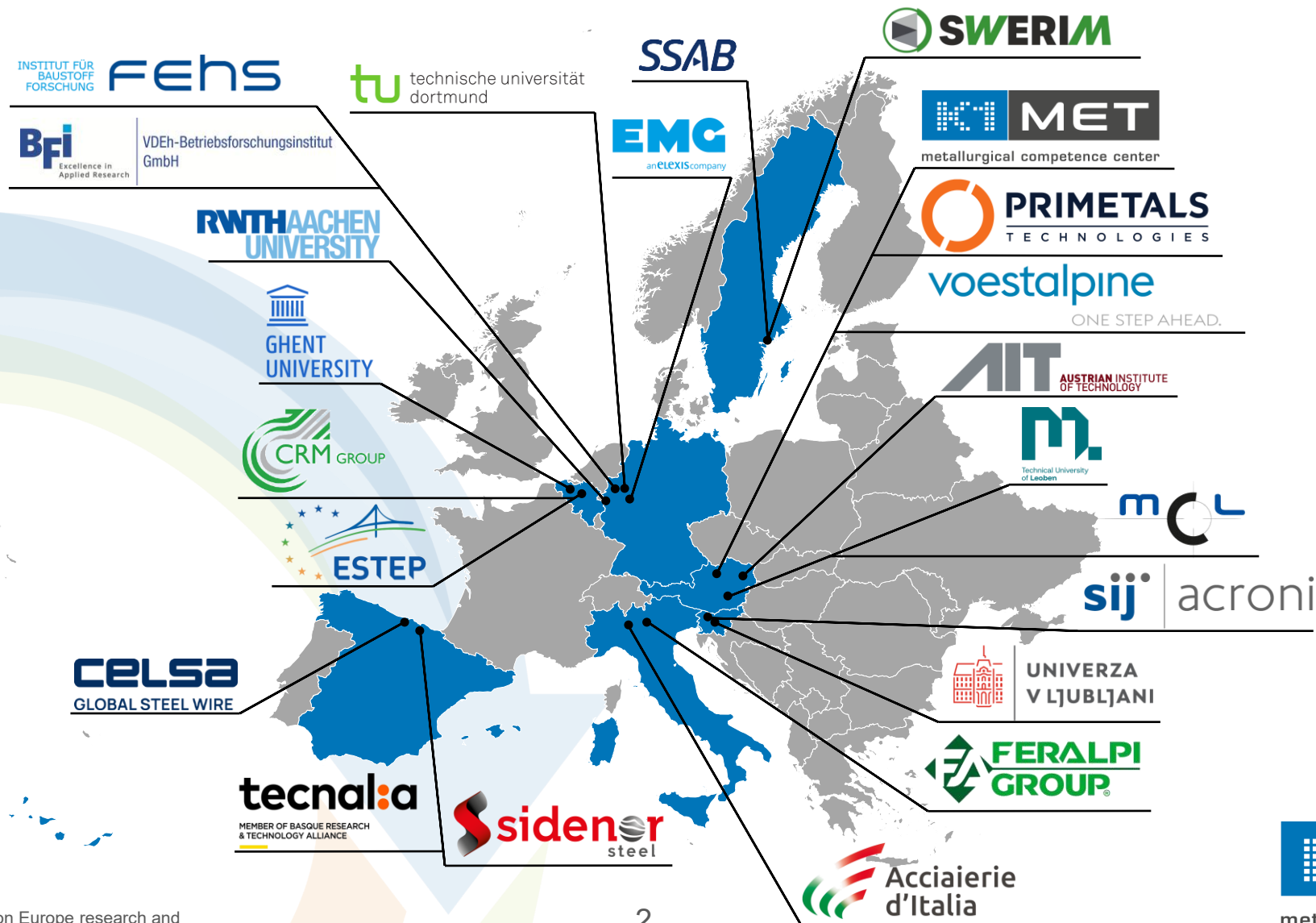


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This project has received funding from the Horizon Europe research and innovation funding program under grant agreement No 101294187.

# Consortium

Meet the CircSmeltSteel Team

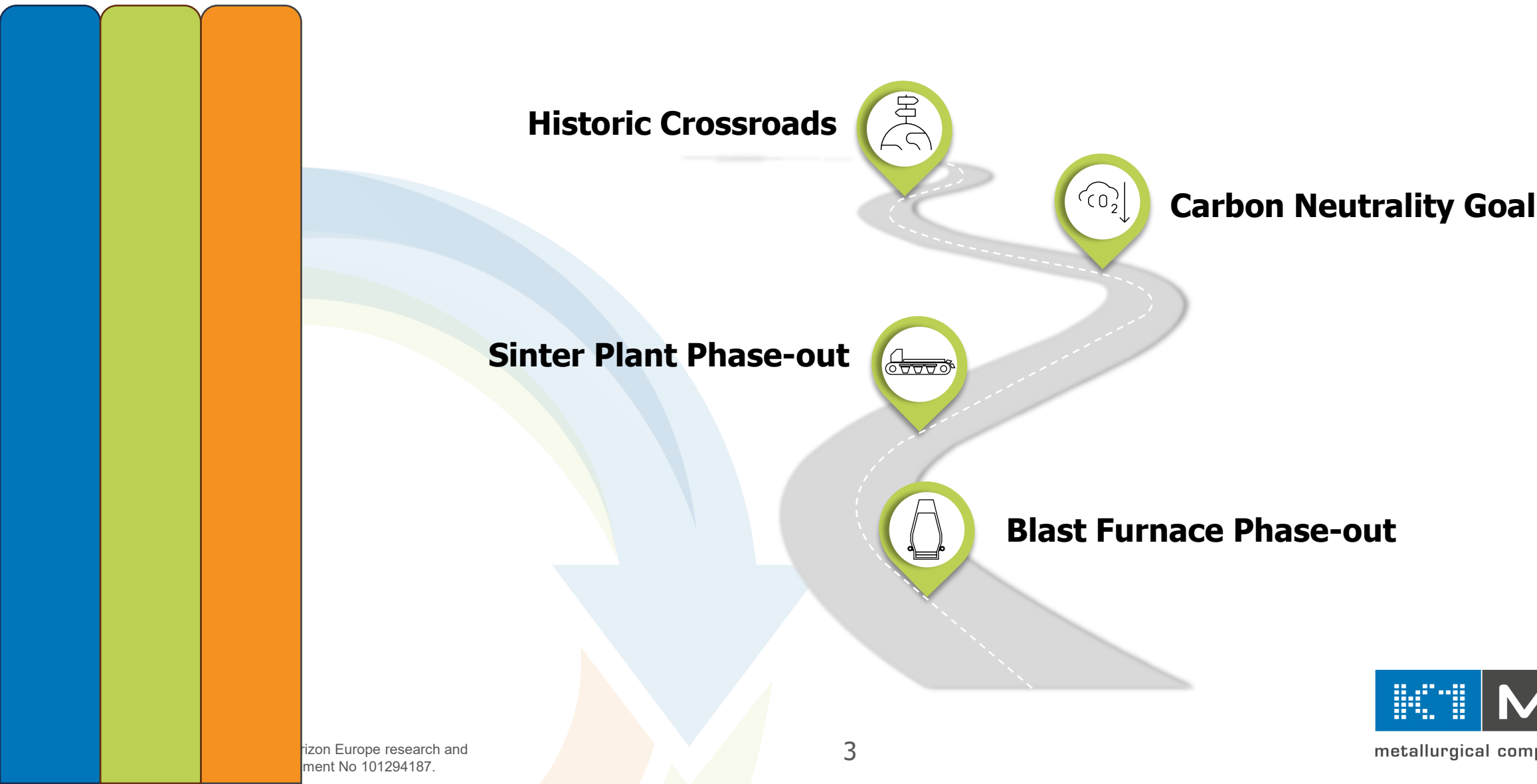


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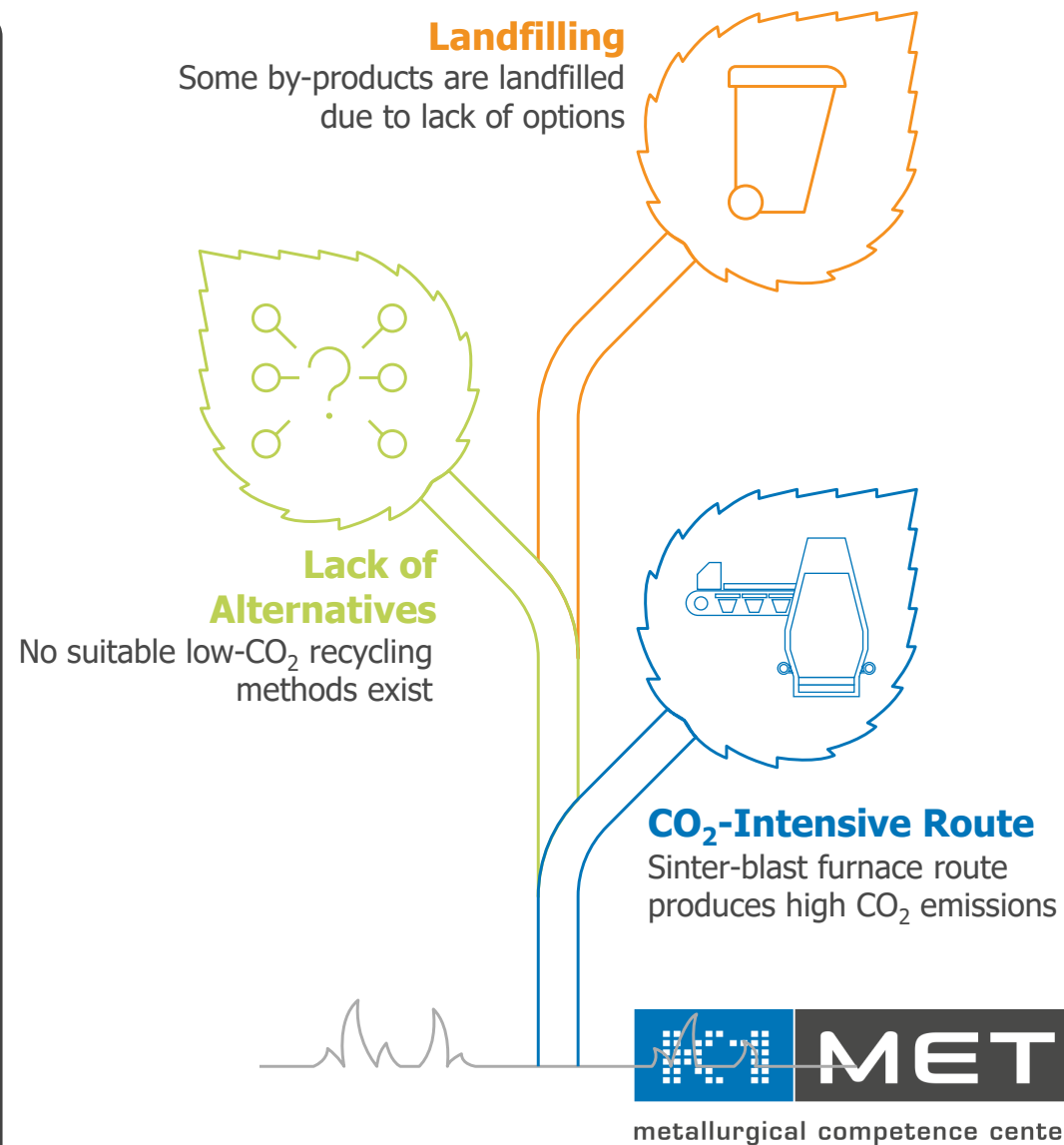
# Challenges of the steel industry's transformation



# Challenges of the steel industry's transformation

## By-product Challenge

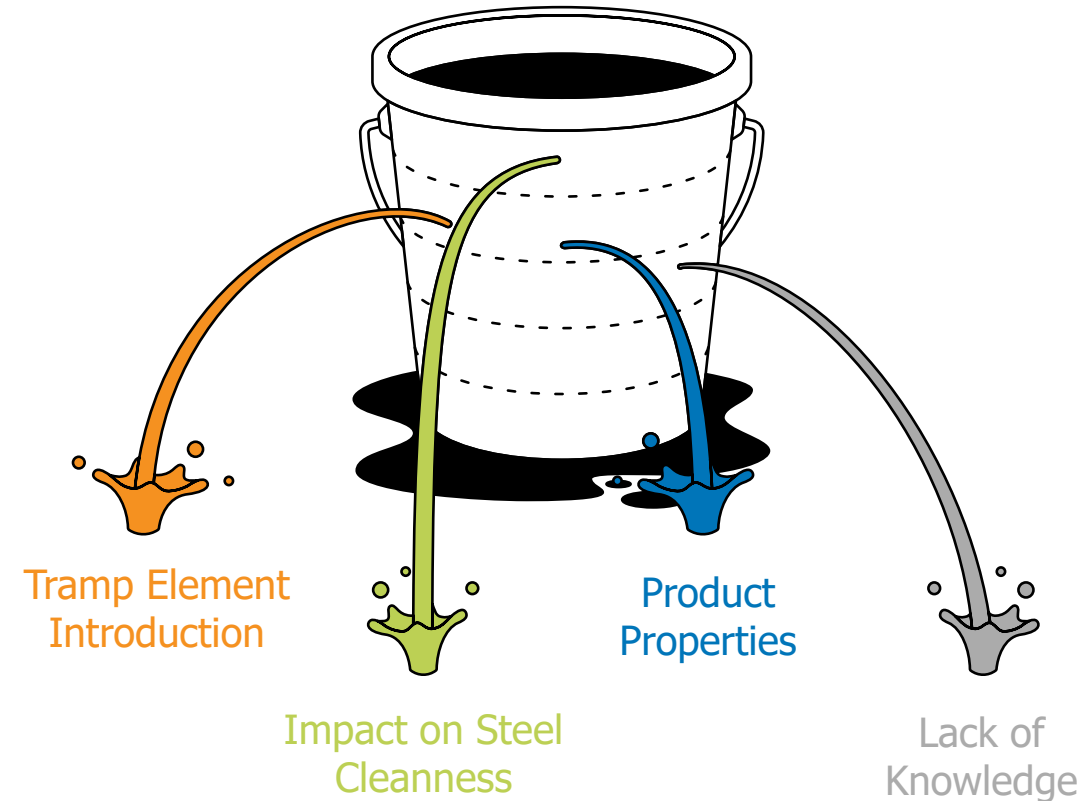
Large volumes of metallurgical by-products (BF dust, BOF slag, EAF dust) are currently recycled via the CO<sub>2</sub>-intensive sinter-BF route or externally treated. As the EU transitions away from integrated BF-BOF plants, low-CO<sub>2</sub> alternatives are urgently needed.



# Challenges of the steel industry's transformation

## Quality Gap

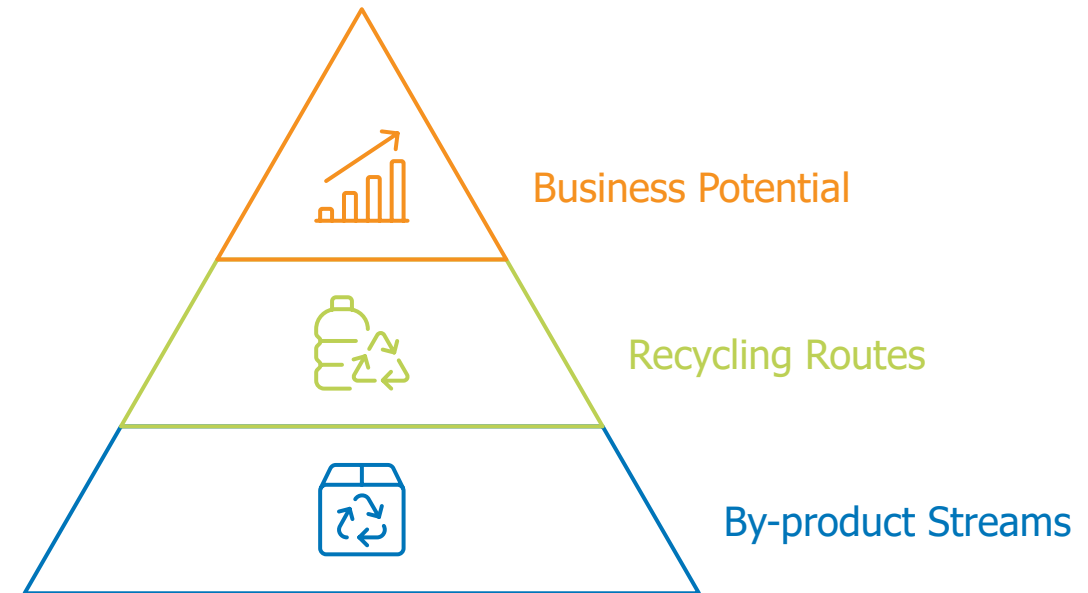
Higher tramp element levels (N, P, S, Cu, Mo, Sn) from low-quality secondary feedstock degrade steel cleanliness. A fundamental lack of knowledge exists on how these elements interact with non-metallic inclusions and final product properties.



# Challenges of the steel industry's transformation

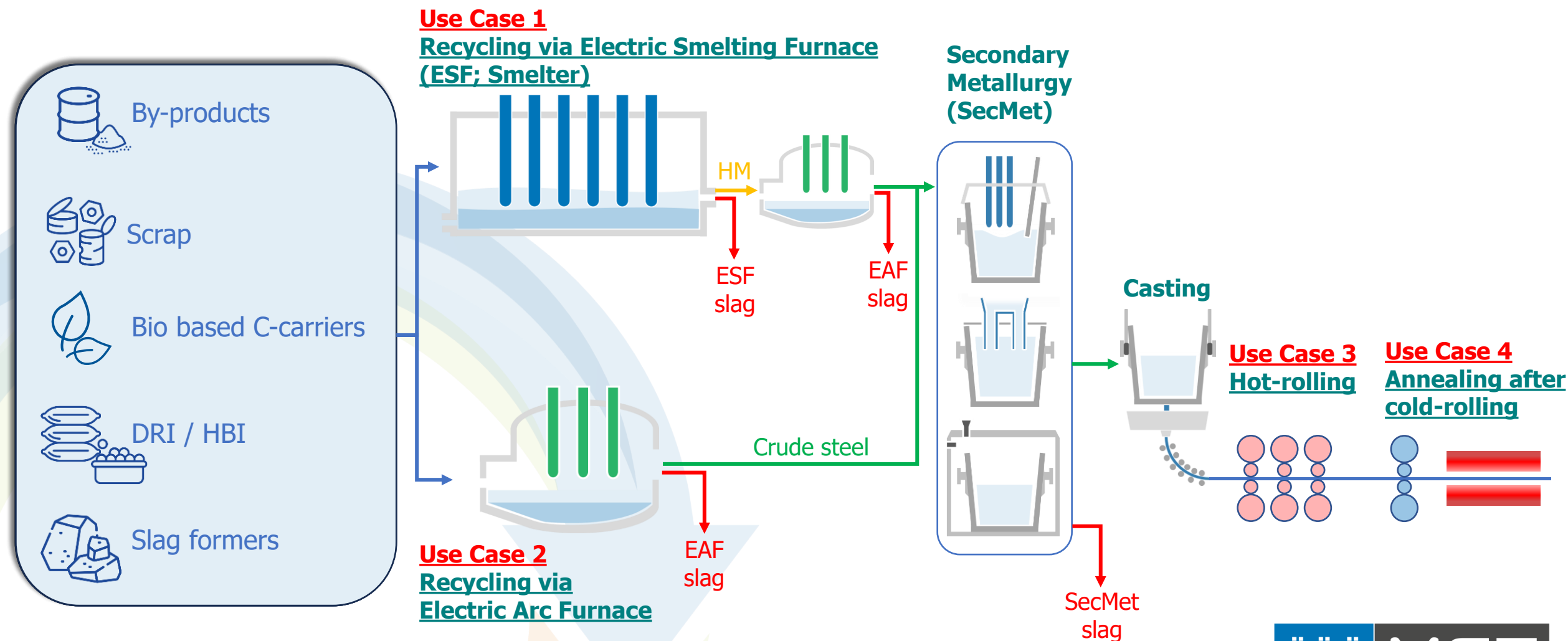
## ~80 Mt Opportunity

Business potential is enormous: ~80 Mt of annual by-product streams are available for recycling via ESF and EAF routes. ESF also has the capability to replace the sinter-BF route in integrated plants.



# The CircSmeltSteel Unique Value

Integrating Upstream & Downstream



# The CircSmeltSteel Unique Value

Upstream: Advanced By-Product Reuse



## By-products

Valorising BF dust, BOF slag, EAF dust, mill-scale, wastewater treatment sludges, AOD dust, EAF & LF slags. Mean Fe content: ~40 wt.-%.



## Pre-Processing

Comparing cold-bonded briquetting (stamp/roller press) and micro-granulation to ensure high-quality furnace input.



## Bio based C-carriers

Integrating non-fossil (bio-based) sources like torrefied wood for final reduction and carburization



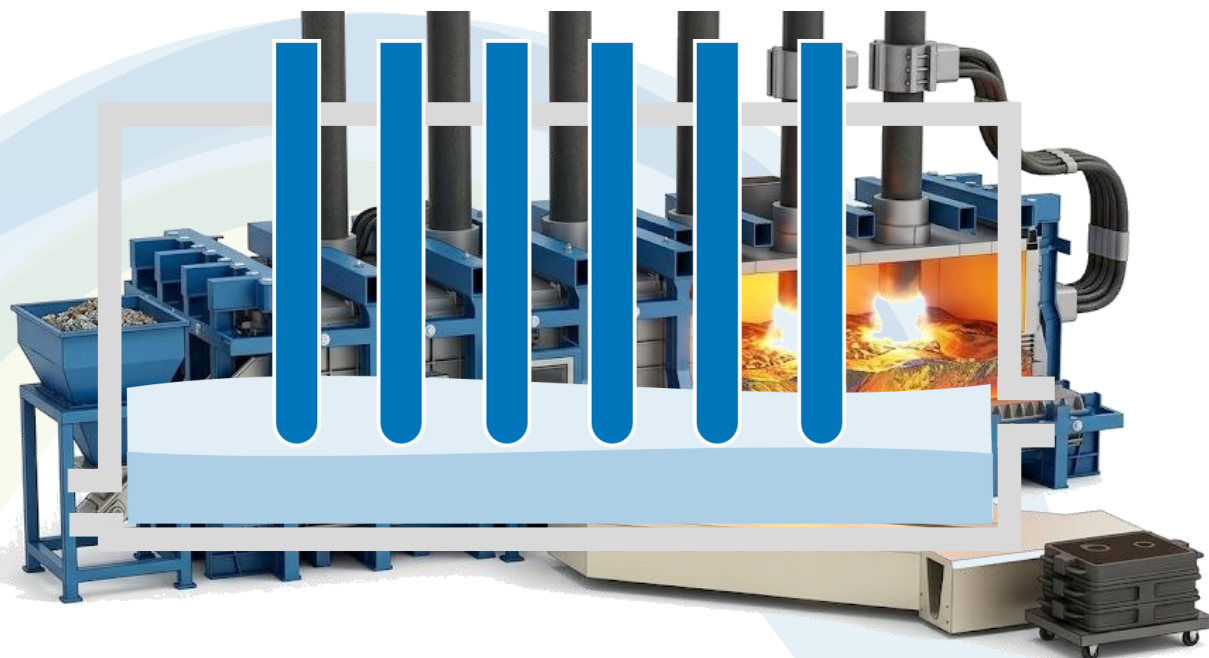
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# Breakthrough Ironmaking: ESF

## Replacing the Blast Furnace

### Use Case 1 Recycling via ESF (Smelter)



The **Electric Smelting Furnace** serves as a low-CO<sub>2</sub> breakthrough technology, producing green HM from DRI/HBI and by-products.

- **CO<sub>2</sub> Reduction:** >80% (Scope 1) vs standard BF
- By-product share: up to **50%** of feed
- **Slag Quality:** Optimized for cross-sectorial use in the cement industry

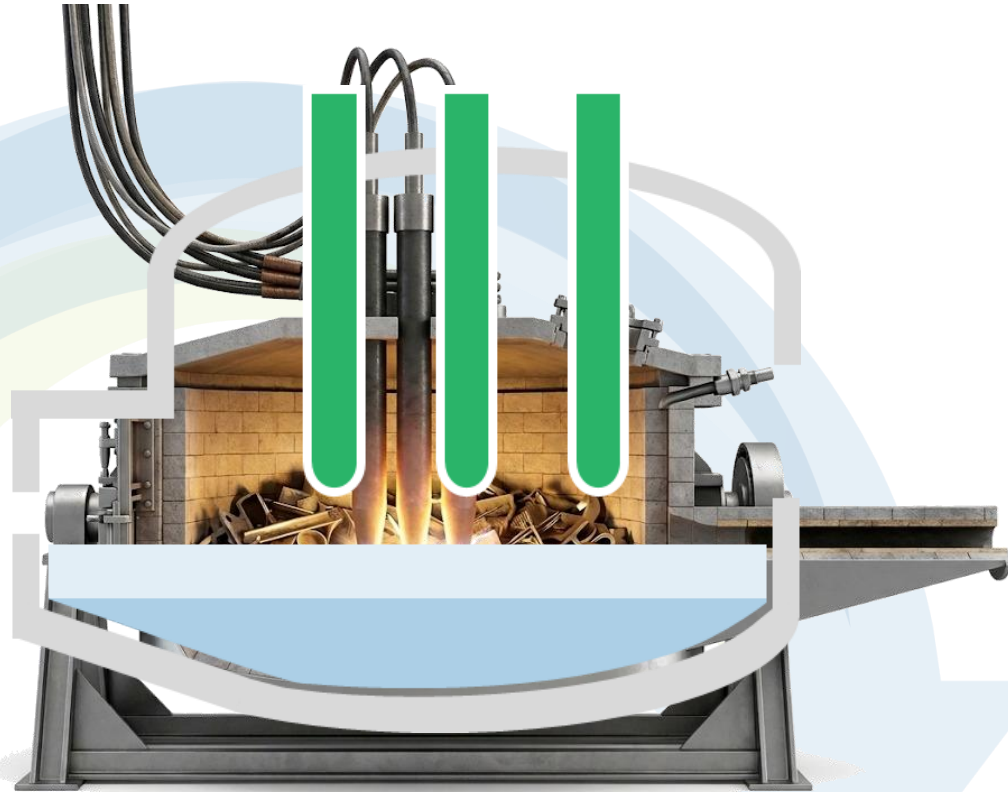
Image generated with Google Gemini; Source: <https://www.primetals.com/en/portfolio/solutions/ironmaking/direct-reduction/smelter/>

# Flexible Steelmaking: The EAF route

Processing of highly contaminated material

## Use Case 2

### Recycling via EAF



Processing ESF-based green HM and low-quality scrap into high-quality crude steel.

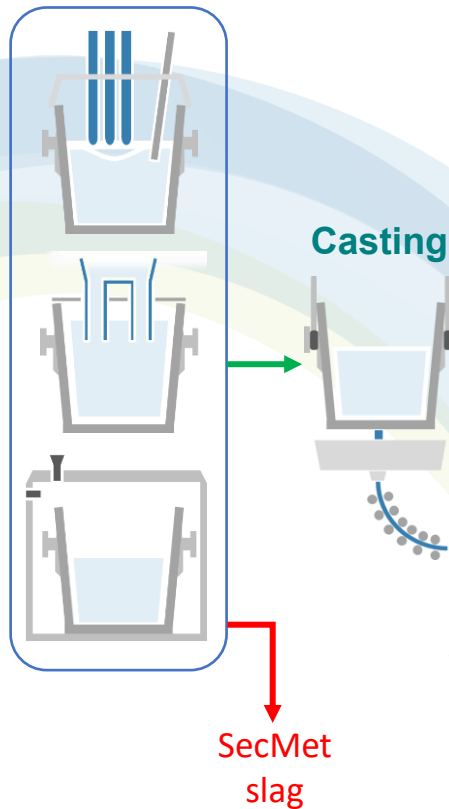
- Comparison of **DC vs AC** operating modes
- By-product share: up to **20%** of crude steel
- Use of **biocarbon** as a slag foaming agent: **25%** direct CO<sub>2</sub> reduction
- EAF slag cleaning for P-separation using **TBRC**

Image generated with Google Gemini; Source: <https://www.cceguide.org/de/technologies/reduce/steel-process-industry/energy-efficiency/electric-arc-furnace/>

# Secondary Metallurgy & Casting

## The Tramp Element Challenge

### Secondary Metallurgy (SecMet)



### Secondary Metallurgy

Higher tramp element inputs require adapted purging, vacuum conditions, time sequences in LF and RH degasser

- RH: enhanced vacuum + Ar injection
- NMI behaviour before/after SecMet analysed via automated SEM-EDS
- HT-LSCM: dissolution of NMIs in SecMet slags

### Casting Sequences & Slab Quality

Tramp elements cause surface cracks on cast slabs

- IMC-B - replicates continuous casting conditions
- STA - matrix damage at grain boundaries
- HT-LSCM - indirect segregation quantification of Cu, Sn, Mo, S, P, N

# Controlling Product Quality

Downstream: Hot-rolling / Annealing after cold-rolling

## Use Case 3 Hot-rolling

## Use Case 4 Annealing after cold-rolling

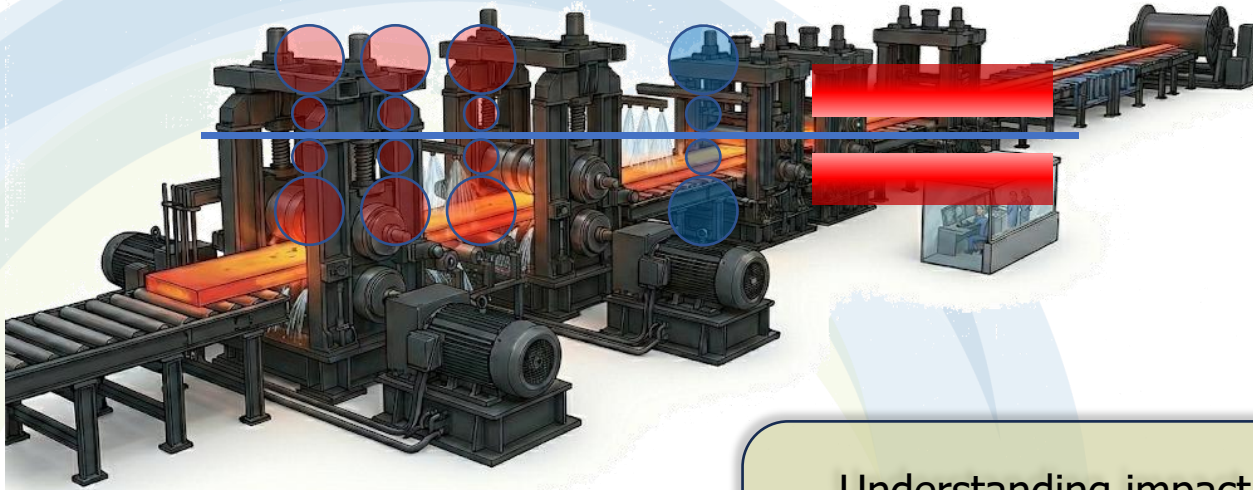


Image generated with Google Gemini

Finishing processes must compensate for upstream chemical variations to reach target properties.

- Hot-rolling simulators used for Flat/Strip/Rod steel
- Annealing cycle optimization for High-Strength Low-Alloy and construction steels
- Inline microstructure analysis using Laser Ultrasound (LUS)

Understanding impact of element variations and process conditions on microstructure and strength + development of material models

# ESF Route – KPIs & Technology Readiness

Specific objectives and measurable targets for the Smelter route

## ESF Route – Key Performance Indicators

|                                            |                       |
|--------------------------------------------|-----------------------|
| By-product share in ESF feed               | <b>up to 50 wt.-%</b> |
| CO <sub>2</sub> reduction (Scope 1 vs. BF) | <b>&gt;80%</b>        |
| Residual FeO in ESF slag                   | <b>&lt;1 wt.-%</b>    |
| Glass content in ESF slag                  | <b>&gt;85 wt.-%</b>   |
| Secondary carbon carriers in ESF           | <b>up to 100%</b>     |
| By-product streams tested                  | <b>≥ 4 streams</b>    |
| Agglomerate recipes developed per route    | <b>≥ 3</b>            |
| TRL advancement – ESF by-product route     | <b>4 → 6</b>          |

## Technology Readiness Level



**Start TRL 4 Target TRL 6**

Prior pilot activity: BOF slag + HBI trials (~750 kg) justify **TRL 4** start. CircSmeltSteel advances to 1 t batch and 2–3 t/h continuous → **TRL 6**.

## Progress Beyond State of the Art

Patent search on ESF/EAF for low-grade Fe-oxide materials: **~120 hits** for pyrometallurgical routes, **0 hits** for electric furnaces → **clear novelty**

**No** prior project investigated by-product shares up to **50 wt.-%** in ESF with complex multi-stream feeds

CircSmeltSteel is **first** to couple ESF-EAF-SecMet-downstream to assess **tramp element impact** on steel quality

# ESF Feedstock & Operating Trial Design

By-product streams and trial matrix

## By-Product Streams

### BOF Slag

**Fe content ~15-25 wt.-%**

Origin: BF-BOF route

### BF Dust

**Fe content ~35-45 wt.-%**

Origin: BF top gas cleaning

### HM Desulph. Slag

**Fe content ~40-60 wt.-%**

Origin: Hot metal treatment

### EAF Dust

**Fe content ~25-45 wt.-%**

Origin: EAF off-gas filter

**Mean Fe content ~40 wt.-% across all streams**

## ESF Operating Trials

| OT | By-Product       | BP Share [%] | Scrap [%] | DRI [%] | Slag former [t/t HM] | Carbon [t/t HM] |
|----|------------------|--------------|-----------|---------|----------------------|-----------------|
| 1  | BOF Slag         | 10           | 20        | 70      | ~0.2                 | ~0.2            |
| 2  | BF Dust          | 25           | -         | 75      | ~0.3                 | ~0.3            |
| 3  | HM Desulph. Slag | 25           | -         | 75      | ~0.3                 | ~0.3            |
| 4  | EAF Dust         | 25           | 20        | 55      | ~0.3                 | ~0.3            |
| 5  | BF Dust          | <b>50</b>    | 20        | 30      | ~0.4                 | ~0.4            |
| 6  | HM Desulph. Slag | <b>50</b>    | 20        | 30      | ~0.4                 | ~0.4            |
| 7  | EAF Dust         | <b>50</b>    | 20        | 30      | ~0.4                 | ~0.4            |

**OT 5–7: maximum by-product share 50 wt.-% – primary target for demonstrating ESF feedstock flexibility**

Carbon carrier: all OT include biocarbon option (up to 100% secondary carbon)

# ESF Pilot Operating Trials

Operating modes, challenges and solutions

## Pilot ESF – Specifications

|                  |                          |
|------------------|--------------------------|
| Furnace type:    | Graphite electrode batch |
| Volume:          | 125 l (1 t batch)        |
| Atmosphere:      | Reducing (airtight)      |
| Operation modes: | Brush-arc / Immersed     |
| HM output:       | Up to 1 t per batch      |
| Facility:        | CRM (Belgium)            |

## Operating Mode Comparison: Brush-Arc vs. Immersed Electrode

### Brush-Arc Mode

- Electrode tip above slag surface
- Arc burns between electrode and slag
- Higher arc voltage → more thermal energy
- More radiation → higher refractory wear risk
- Preferred: high slag volume, early melt phase
- Lower reducing potential near bath surface

### Immersed Electrode Mode

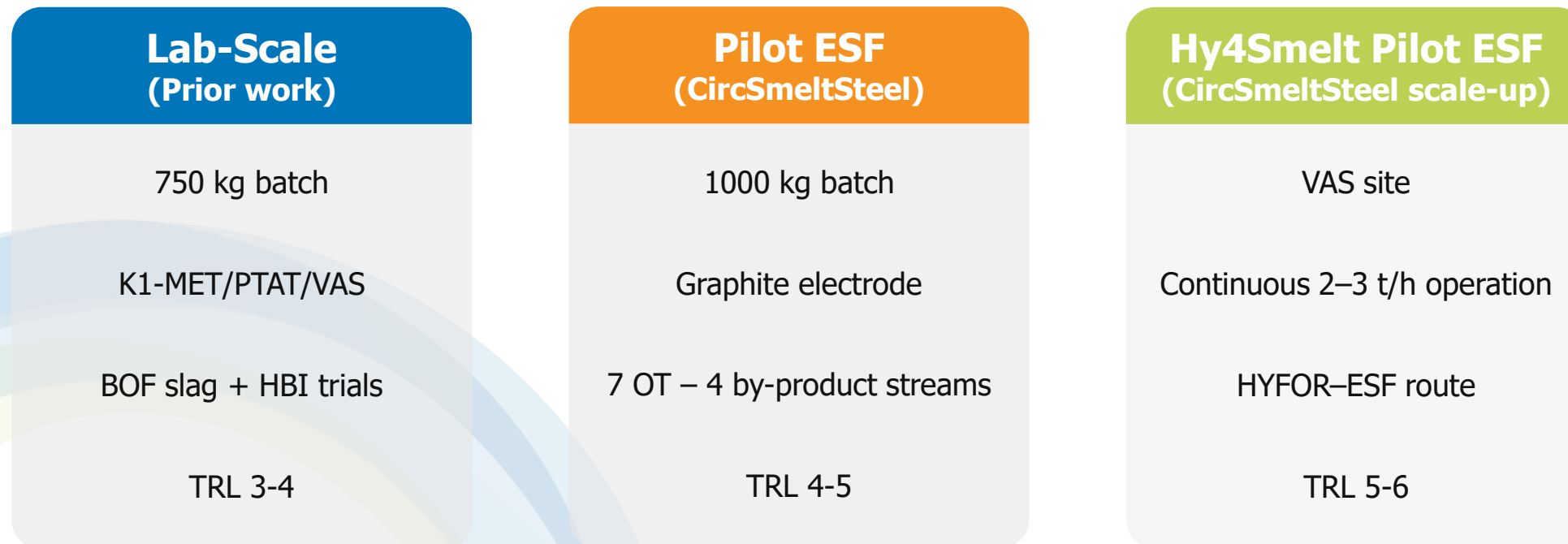
- Electrode tip submerged in slag
- Resistive heating via slag column
- More homogeneous energy input
- Strongly reducing conditions at slag-metal interface
- Minimises residual FeO in slag
- Preferred: final reduction, high FeO slag feeds

### Central research question:

How do brush-arc vs. immersed electrode modes affect Fe yield, residual FeO in slag, and hot metal chemistry when processing by-products at shares up to 50% in the ESF feed?

# Scale-Up: Pilot → Continuous ESF

TRL 4→6: Validation at semi-industrial scale



## Hy4Smelt Pilot ESF – Context & Relevance for CircSmeltSteel

- RFCS Big Tickets project (Clean Steel Partnership, GA 101193416, 2025–2029): establishes HYFOR–ESF continuous hot metal route
- VAS site: 2–3 t/h continuous ESF – CircSmeltSteel plans at least 1–2 campaigns with by-product agglomerates
- Batch results (1 t) validated under continuous conditions → provides industrially relevant TRL 6 evidence

# Process Modelling – Thermodynamic & Dynamic Model

Slag design and industrial-scale extrapolation

## Thermodynamic Slag Optimisation

### FactSage™ & Thermo-Calc™

#### PRE-TRIAL

- Optimal slag former addition rates calculated for each OT
- Liquidus temperatures, solid phase precipitation prediction during cooling

#### POST-TRIAL

- Calculated phase evolution validated against measured compositions
- Cross-validation: FactSage™ and Thermo-Calc™ run in parallel

## Dynamic ESF Process Model

### Mass & Energy Balances

Time-resolved mass and energy flows through the ESF; coupled slag and metal phase balance for each OT scenario

### Thermochemical Sub-Model

FeO reduction kinetics, Fe carburisation, carbon gasification; directly linked to FactSage™/Thermo-Calc phase diagram outputs

### Slag Property Sub-Model

T- and composition-dependent viscosity and electrical conductivity inputs from measurements

### Operating Mode Module

Both brush-arc and immersed electrode modes modelled; scenarios validated against OT data

### Scale-Up Module

Extrapolation: 1 t batch → 2–3 t/h continuous → fully industrial scale; key output for exploitation

# Expected Outcomes & Summary

Scientific and industrial impact of the CircSmeltSteel ESF route

1

## Clear industrial motivation

Phase-out of BF-BOF creates urgent gap; ESF closes it – compatible with existing BOF, targets >80% CO<sub>2</sub> reduction. By-products with ~40 wt.-% Fe: significant secondary iron source

2

## Systematic 7-trial programme

4 by-product streams; feed shares 10–50 wt.-%; briquettes vs. micro-granules; induction melting, TG, DSC pre-screening; 7 ESF-OT including 3 trials at maximum 50 wt.-% share

3

## Novel scientific contributions

First dataset on ESF slag electrical conductivity; systematic brush-arc vs. immersed electrode comparison; agglomerate performance database under ESF reducing conditions

4

## Clear TRL scale-up pathway

CRM 1 t batch (TRL 4–5) → Hy4Smelt 2–3 t/h continuous (TRL 6); validated at industrially relevant scale by project end; 7–8 years consortium ESF experience

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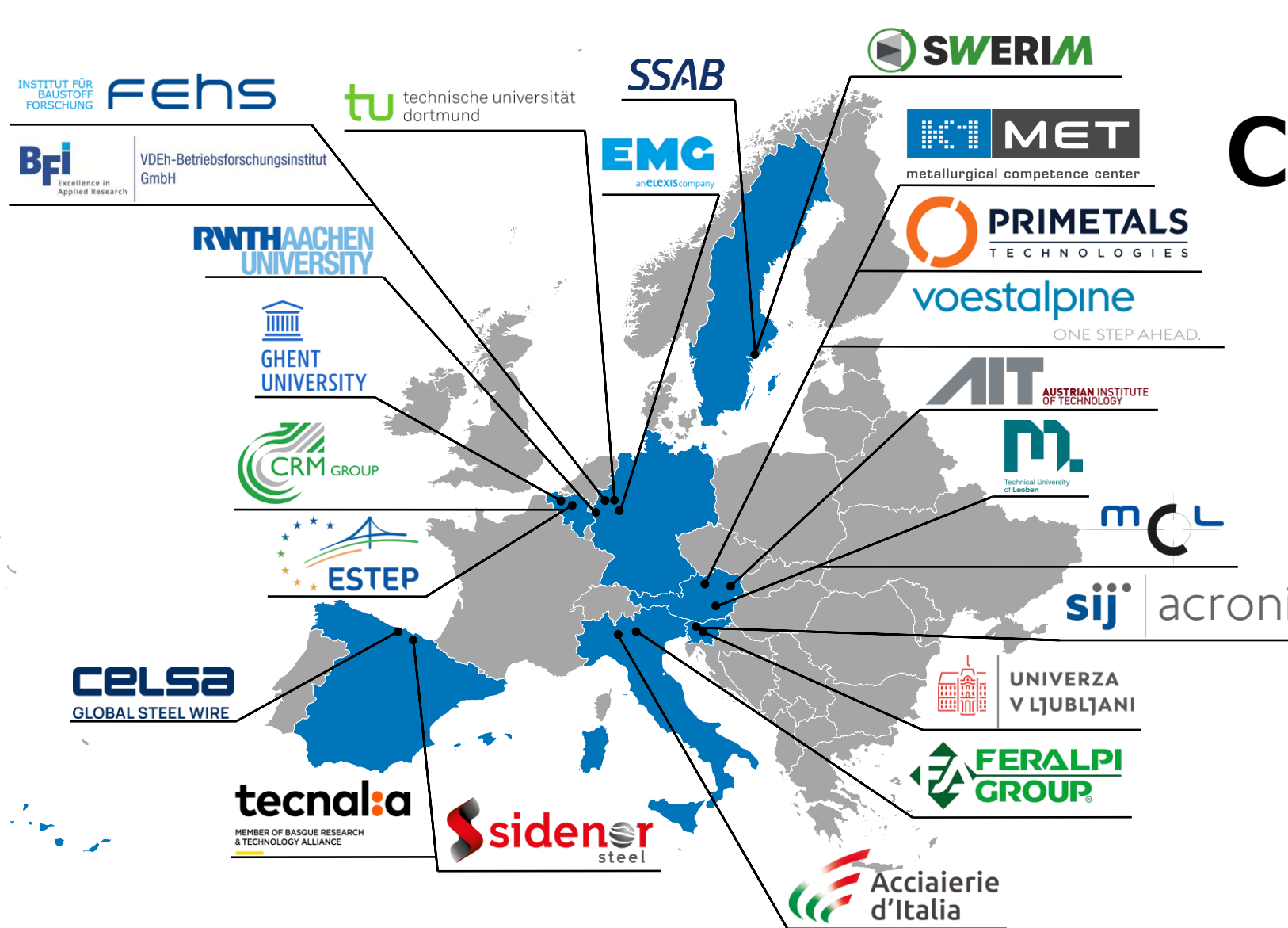
## Integrated valorisation chain

Thermodynamic slag design; slag viscosity & conductivity; cement SCM assessment & dry granulation; full downstream coupling (SecMet, casting, rolling)

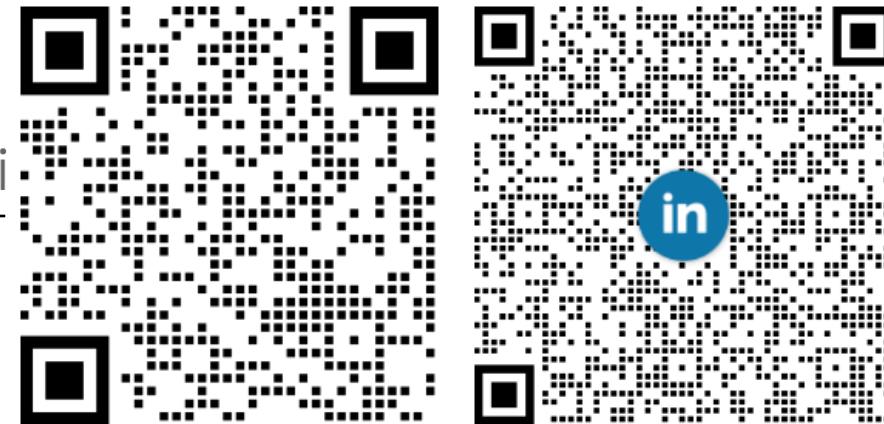
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## Quantitative KPI targets

>80% CO<sub>2</sub> reduction (Scope 1); <1 wt.-% FeO in ESF slag; >85 wt.-% glass content for cement; up to 50 wt.-% by-product share; up to 100% secondary carbon; TRL 4→6



# CircSmeltSteel



# Thank you!



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