ESTEP SPRING DISSEMINATION EVENT

5-6 JUNE 2025 KRAKOW (POLAND)

Overview of the first 1½ years of the Horizon EU project H2PlasmaRed

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ESTEP

HOTEL GALAXY JORDAN GROUP

Łukasiewicz GIT

H_2 reduction of iron ore

a) Direct reduction

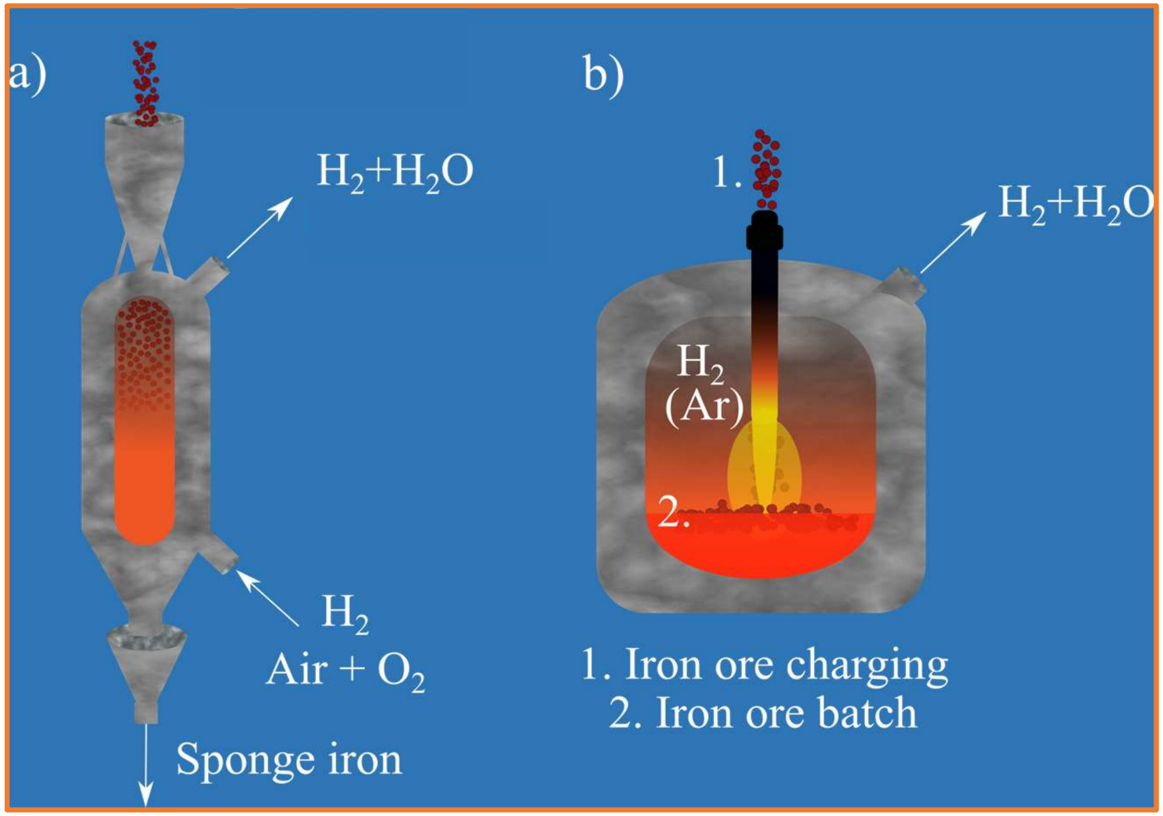
- H_2 gas is introduced to a shaft furnace (bottom) with iron ore (top)

$$3Fe_2O_3 + H_2 \rightarrow 2Fe_3O_4 + H_2O$$
$$Fe_3O_4 + H_2 \rightarrow 3FeO + H_2O$$
$$FeO + H_2 \rightarrow Fe + H_2O$$

b) Plasma smelting reduction

- Iron ore is smelted and reduced in a single-step process with electricity (plasma arc)

$$H_2 \rightarrow H, H^*, H^+, e^- = HP$$
$$Me_xO_y + HP \rightarrow xMe + yH_2O$$



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Hydrogen plasma smelting reduction at Max Planck, Düsseldorf (April 2024)

H2PlasmaRed – project details

Hydrogen Plasma Reduction for Steelmaking and Circular Economy

Coordinator contact: Dr. Henri Pauna

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Consortium
13 partners and 1 associated partner

Budget
6.3 M€

Duration
01.01.2024 – 31.12.2027

Oulu's team in H2PlasmaRed

Process metallurgy research unit

Dr. Henri Pauna
Project coordinator

Prof. Timo Fabritius

Assoc. Prof. Ville-Valtteri Visuri

M. Sc. Henna-Riikka Putaala

M. Sc. Areej Javed

Nano and molecular systems research unit

Prof. Marko Huttula

Dr. Samuli Urpelainen

M. Sc. Laura Jussila

Research and project services

Irja Ruokamo
Administrative support

Pekka Räsänen
IPR support

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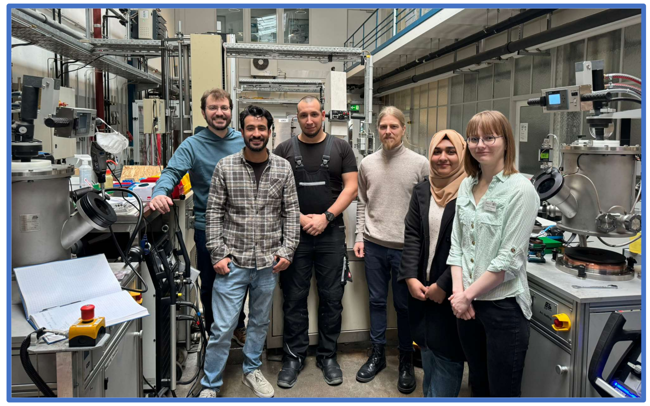
H2PlasmaRed – lab-scale reactors

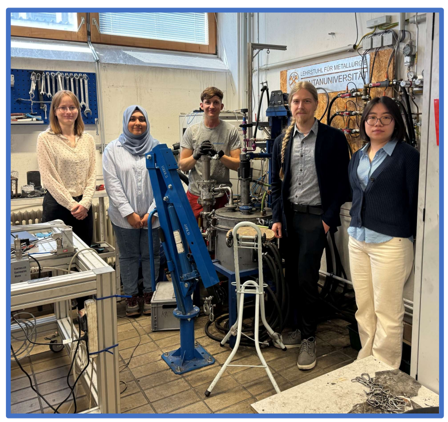
Lab-scale H_2-plasma campaign at Max Planck Institute in March-April 2024

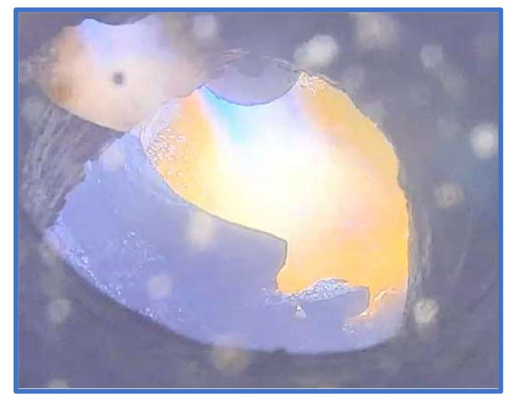
- 10-20 g sample size



Lab-scale H_2-plasma campaign at Montanuniversität Leoben in May 2024

- 100-200 g sample size





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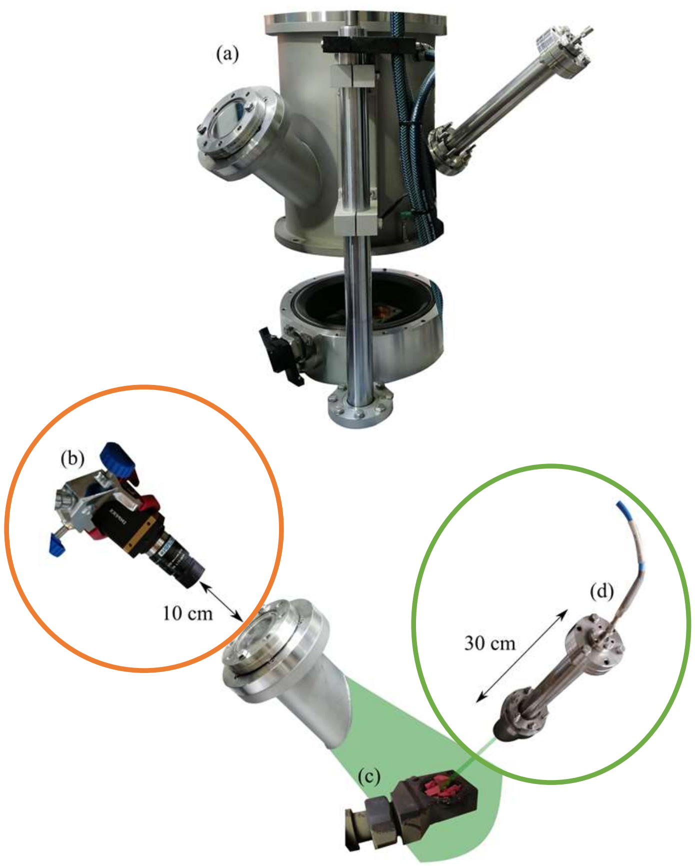
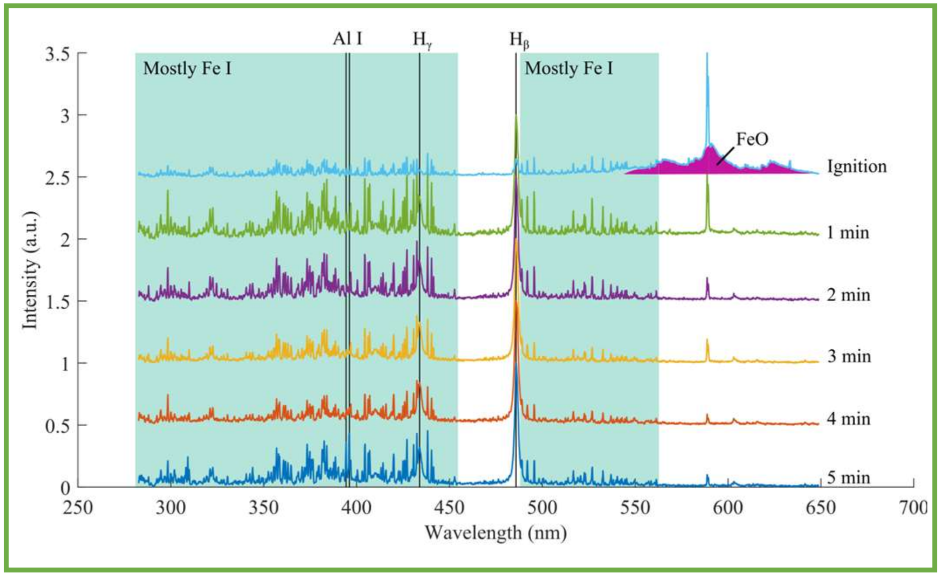
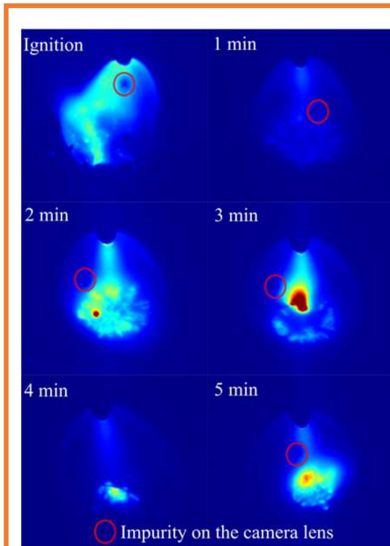
Case study 1 – H_2-plasma monitoring with OES







(a) H_2-plasma reactor at Max Planck Institute, Düsseldorf

(b) Camera with bandpass filter for measuring radiation from atomic iron

(c) Crucible

(d) Optical fiber to measure optical emissions spectra (OES)

- High-energy plasma radiates light with element-specific wavelengths
  → we measure this light to analyze the plasma

Image source: Pauna et al., In Situ Observation of Sustainable Hematite-Magnetite-Wüstite-Iron Hydrogen Plasma Reduction, Metallurgical and Materials Transactions B, 2024, DOI: 10.1007/s11663-025-03610-y

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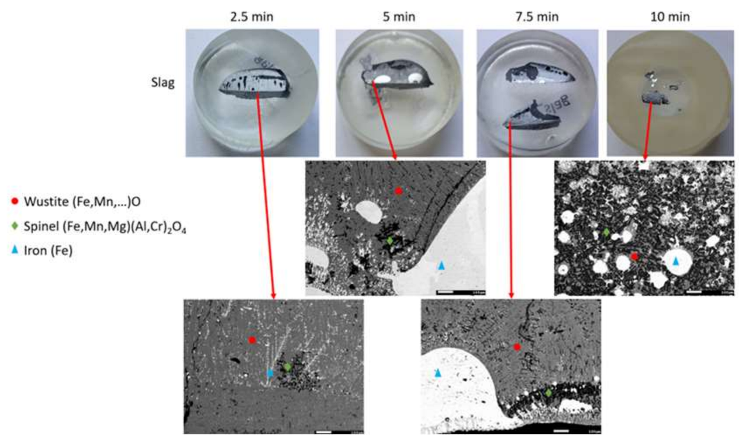
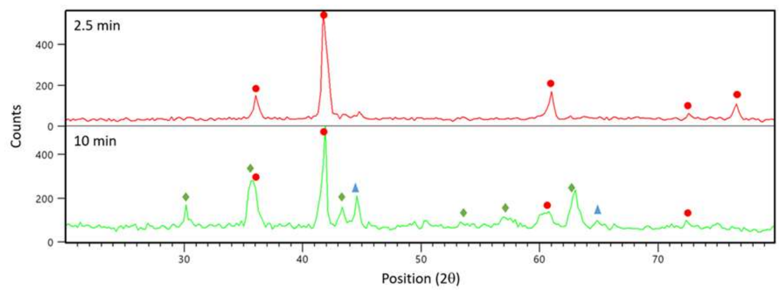
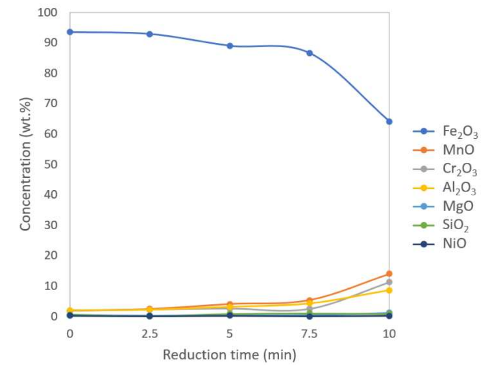
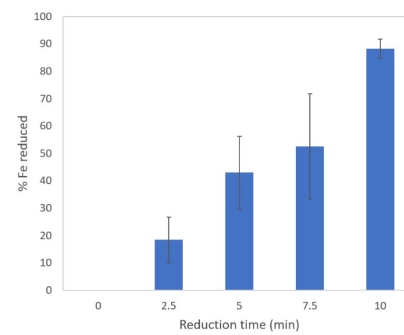
Case study 2 – Hematite-rich leach residue

- Four 10 g samples with 2.5, 5, 7.5, and 10 min H2-plasma reduction









Baseline definitions for HPSR in steelmaking and sidestream treatment, *WP1 Process analysis, characterization, and baseline definitions*, Deliverable D1.2, H2PlasmaRed project (Hydrogen Plasma Reduction for Steelmaking and Circular Economy), 2024, https://h2plasmared.eu/

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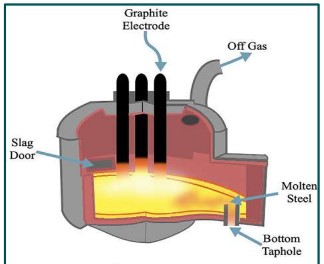
Case study 3 – Critical Metals Recovery

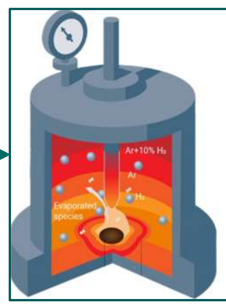


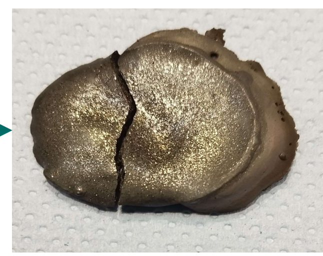
EAF/AOD

SS Dust

Pellets

HPSR





Recovered metal

- Dust from **Electric Arc Furnace (EAF)** and **Argon Oxygen Decarburization (AOD)** vessel is collected from the roof of EAF and above the AOD opening, respectively.
- The dust is dried in a furnace for 24 hours at 150 ^oC.
- Pellets are prepared and reduced by Hydrogen Plasma Smelting Reduction (HPSR) with 10%H_2.

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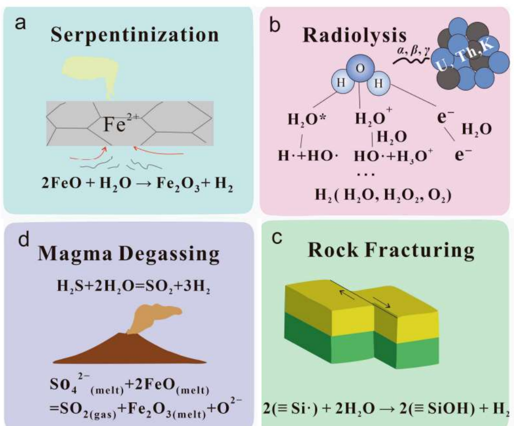
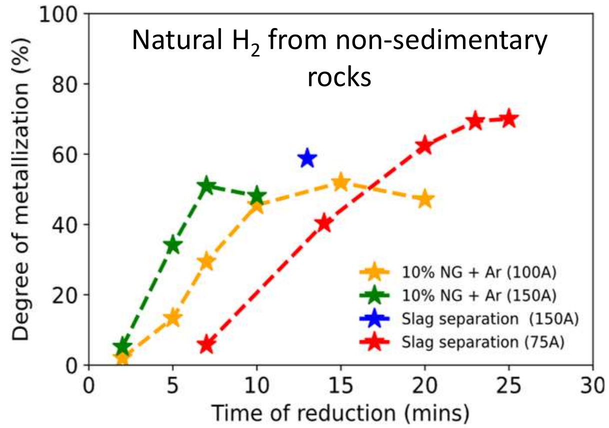
Case study 4 – Varying H_2 sources

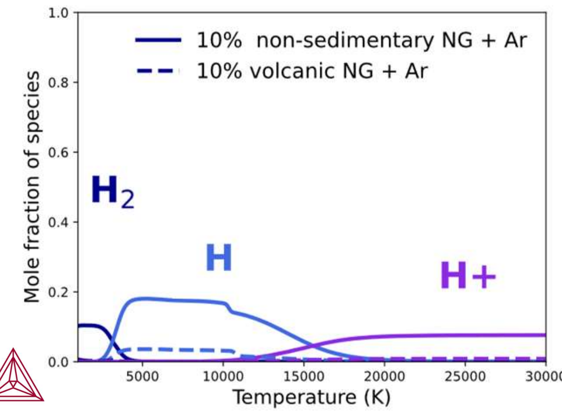


Sources
Non-sedimentary rocks
Volcanic origin

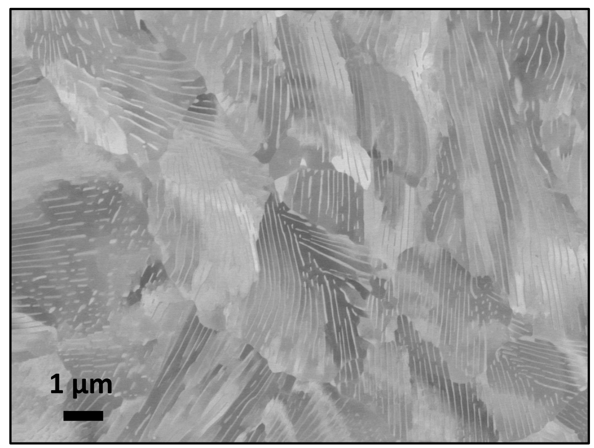
Reduction kinetics optimization



Not all natural hydrogen mixtures work!! But why??



How do the elements partition?



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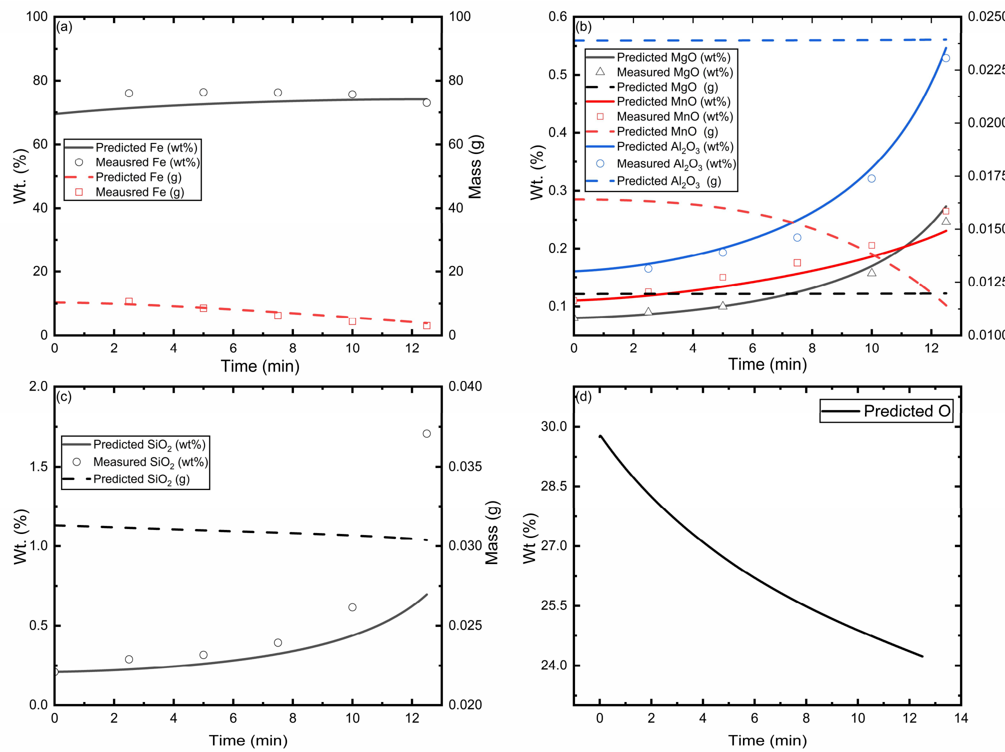
Case study 5 – mathematical modeling

- The metal-slag reaction module describe the kinetics of mass transfer-controlled reactions in the presence of the plasma species
- The gas phase is introduced into the system, including reactive gas species (H, H_2, O, H_2O, Ar) to simulate the effects of hydrogen plasma interactions
- The distribution and activity of oxygen at the reaction interface is solved using the effective equilibrium constant method on the basis of equilibrium constants and mass transfer coefficients in respective phases.
- Numerical time integration of the mass change of each component using the explicit 4th order Runge-Kutta-Fehlberg method (RKF45).



Validation using pure hematite reduction experiments

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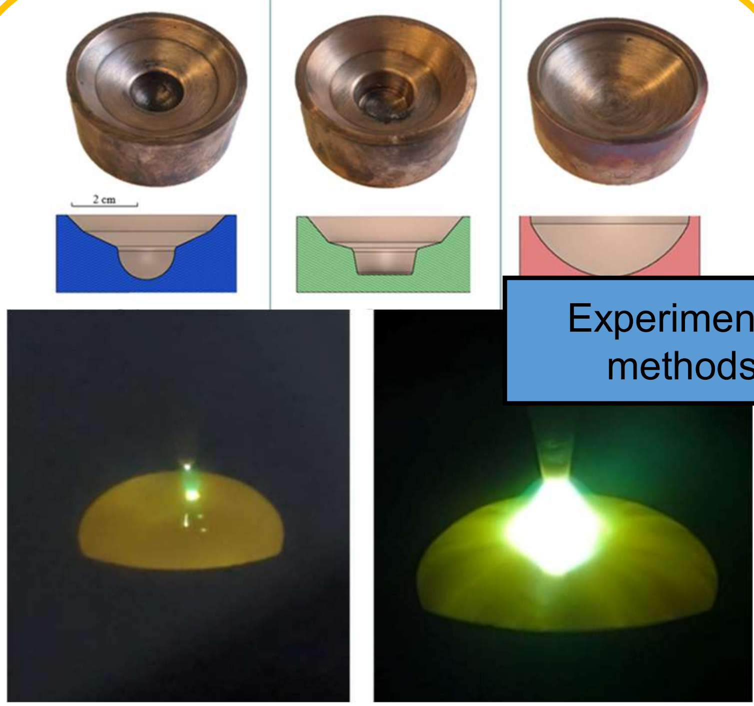
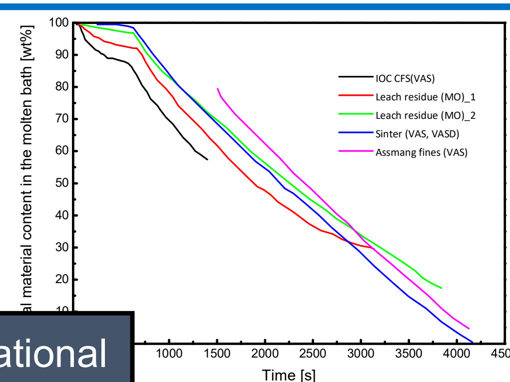
Case study 6 – HPSR process optimization

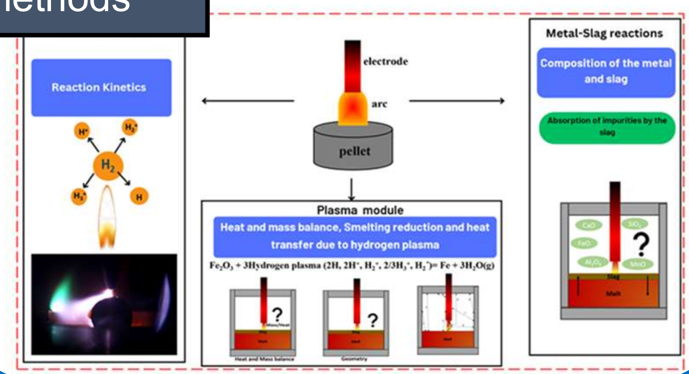
Development of process optimization of H_2-plasma-based steelmaking and side stream treatment by online data analysis and modeling



Experimental methods

Computational methods





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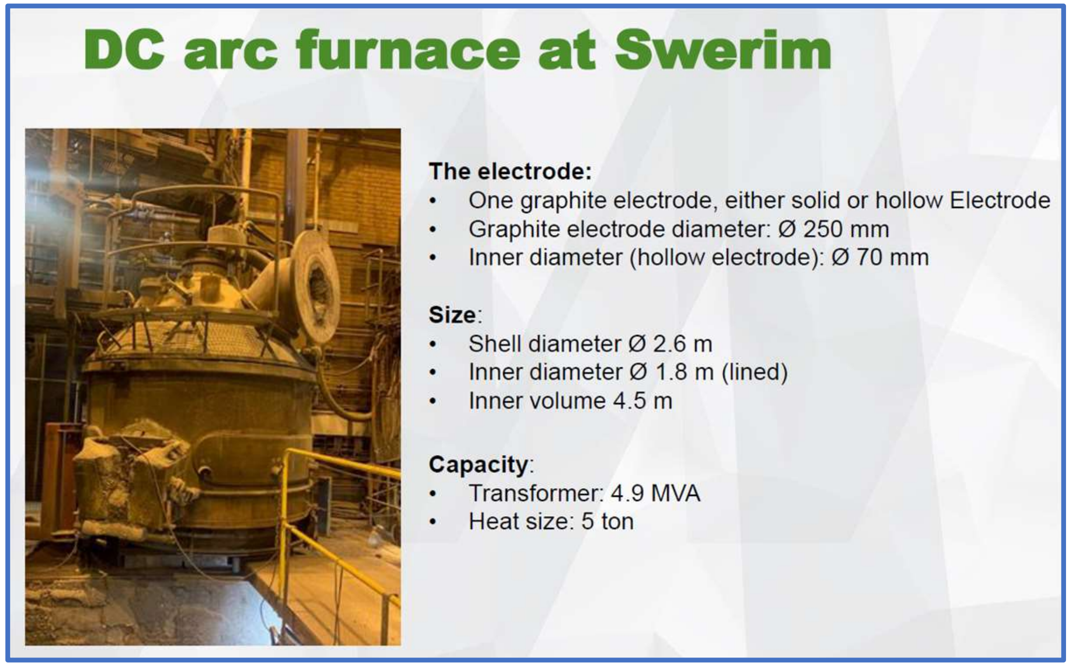
Demonstration reactors at K1-MET and Swerim

Pilot trials at K1-MET GmbH will take place
06-12/2025

Pilot trials at Swerim AB will take place
06/2026



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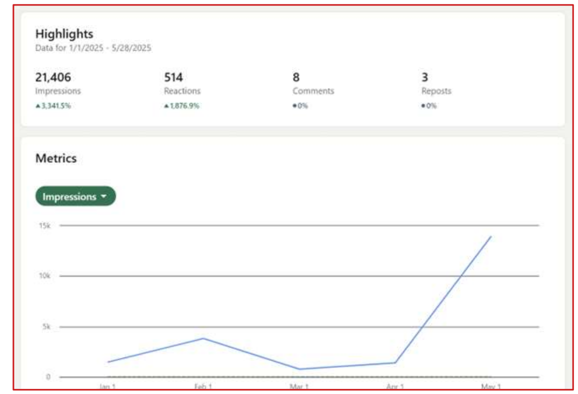
Communication, Dissemination, Publications



ACTIVITIES

- Publishing on project website & LinkedIn page [currently 400 followers]
- Slag Valorization Symposium 8 – 11 April 2025 (Leuven)
- ESTEP Spring Dissemination Event – 5th -6th June 2025 (Krakow) – Overview of the first $1^{1/2}$ years of the Horizon EU project H2PlasmaRed (Henri Pauna)
- 1st Newsletter (work in progress with help from ESTEP) – we aim for a publish date: end of June 2025 - 2nd Newsletter – coming beginning of December 2025
- Magazine article – Steel Times International (drafted by ESTEP and University of OULU) – submission expected in July 2025

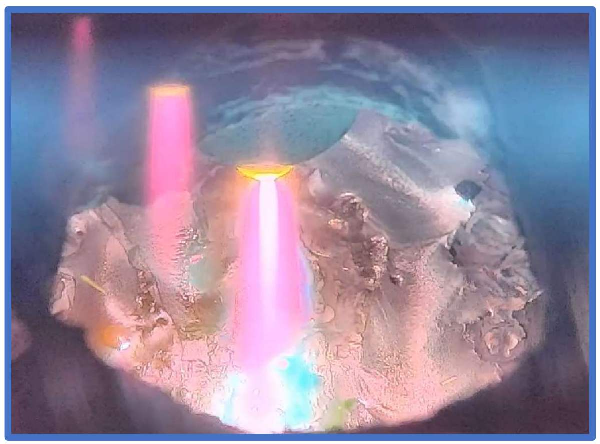
PUBLICATIONS

- SAM19 2025 – [Abstract] A review on environmental and economic assessments of emerging steel manufacturing technologies
- EASES 2025 – [Abstract] Kinetic Modelling of Hematite Reduction by Hydrogen Plasma Smelting Reduction in laboratory scale
- SVS25 – [Poster] A review on environmental and technoeconomic assessments of natural gas based direct reduced iron production path
- ICS 2025 [Abstract] Characterization of high-temperature hydrogen technologies at the University of Oulu
- ICS 2025 [Abstract] Effect of dust on optical emission spectra of hydrogen plasma reduction

Two first peer reviewed articles:

H.-R. Putaala *et al.*, *Effect of Furnace Parameters on Optical Emission Spectra of Hematite Reduction by Hydrogen Plasma*, https://doi.org/10.3390/met10091117
H. Pauna *et al.*, *In Situ Observation of Sustainable Hematite–Magnetite–Wüstite–Iron Hydrogen Plasma Reduction*, https://doi.org/10.1007/s11663-025-03610-y

Hydrogen plasma reduction for steelmaking and circular economy – H2PlasmaRed



Thank you!

Contact: Dr. Henri Pauna
Email: henri.pauna@oulu.fi

H. Pauna et al., *In Situ Observation of Sustainable Hematite–Magnetite–Wüstite–Iron Hydrogen Plasma Reduction,* Metallurgical and Materials Transactions B (2025).

H. Pauna et al., The Optical Spectra of Hydrogen Plasma Smelting Reduction of Iron Ore: Application and Requirements, *Steel Research Int.* 2400028 (2024).

H. Pauna et al., Hydrogen plasma smelting reduction process monitoring with optical emission spectroscopy – Establishing the basis for the method, *Journal of Cleaner Production,* 372, 133755 (2022).

H. Pauna et al., Towards on-line slag composition analysis – optical emissions from laboratory electric arc, *Metallurgical and Materials Transactions B*, 53, 454-465 (2021).

H. Pauna et al., Quantifying the CaO and CaF_2 Content of Industrial Ladle Furnace Slag with Optical Emissions Measured through the Casting Spout, *Steel Research International*, 2100519 (2021).

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H. Pauna et al., Optical emission spectroscopy as an on-line analysis method in industrial electric arc furnaces, *Steel Research International*, 91(11): 2000051 (2020).

H. Pauna et al., Electric Arc Length-Voltage and Conductivity Characteristics in a Pilot-Scale AC Electric Arc Furnace, *Metallurgical and Materials Transactions B*, 51B: 1646 (2020).

H. Pauna et al., Pilot-scale AC electric arc furnace plasma characterization, *Plasma Research Express*, 1(3): 035007 (2019).

M. Aula et al., On-line Analysis of Cr2O3 Content of the Slag in Pilot Scale EAF by Measuring Optical Emission Spectrum of Electric Arc, *ISIJ International*, 57(3): 478-486 (2017).

M. Aula et al., Optical Emission Analysis of Slag Surface Conditions and Furnace Atmosphere during Different Process Stages in Electric Arc Furnace EAF, *ISIJ International*, 55(8): 1702-1710 (2015).

M. Aula et al., Analysis of Arc Emission Spectra of Stainless Steel Electric Arc Furnace Slag Affected by Fluctuating Arc Voltage, *Applied Spectroscopy*, 68(1): 26-32 (2014).

M. Aula et al., Characterization of Process Conditions in Industrial Stainless Steelmaking Electric Arc Furnace Using Optical Emission Spectrum Measurements, *Metallurgical and Materials Transactions B*, 45(3): 839-849 (2014).

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