Hydrogen-Based Direct Reduction of Iron Ore Pellets: Kinetic Assessment of an Integrated DR-EAF Route

Alessandro Torri, Daphne Mirabile, Valentina Alemanno and Filippo Cirilli

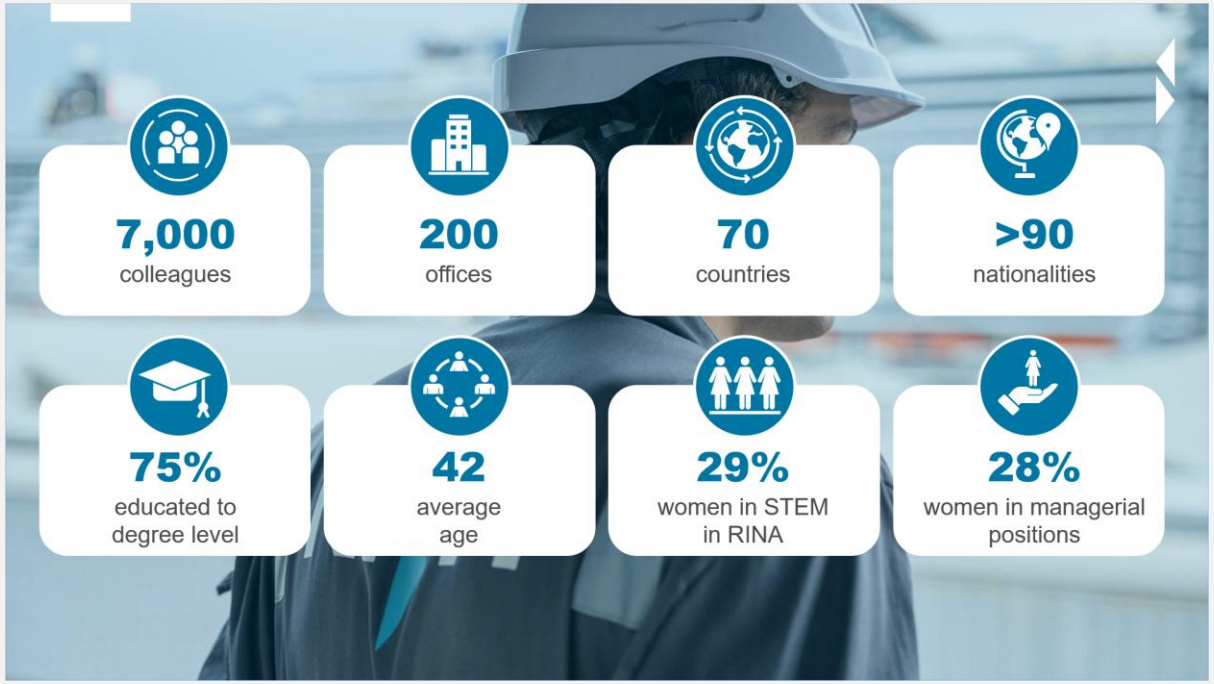
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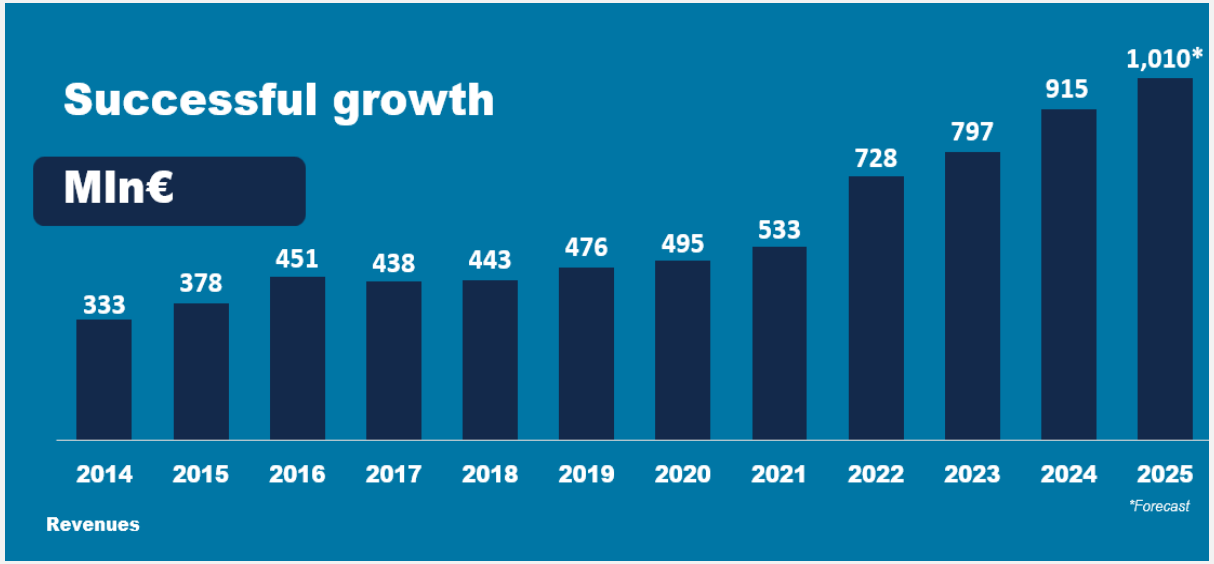


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RINA CSM

RINA CSM

- The **Rina Industry Business Unit** provides high-added value integrated services with a special focus on manufacturing, steel and heavy industry, aerospace and defense.

- **Whitin this BU, RINA CSM** is the Company devoted to the Steel Industry and manufacturers in sectors such as Oil&Gas, Power Gen and Automotive.

- **RINA CSM** was founded in 1963 by Italian Government and since 2013 incorporated in **RINA Group**.

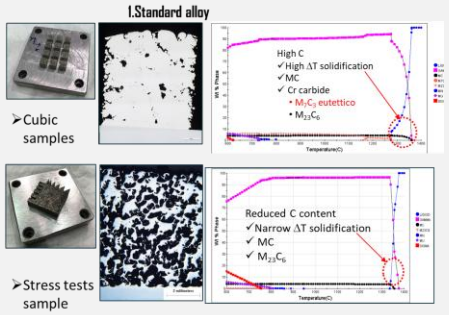
- More than **270** highly trained and **experienced resources** and **11 laboratories and pilot plants**

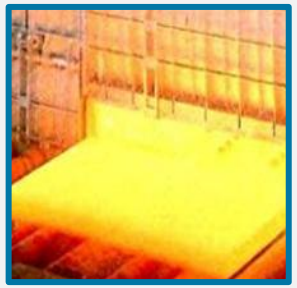
- More than **300 R&D projects per year** for the most important European steel makers, plant suppliers, Oil&Gas majors.

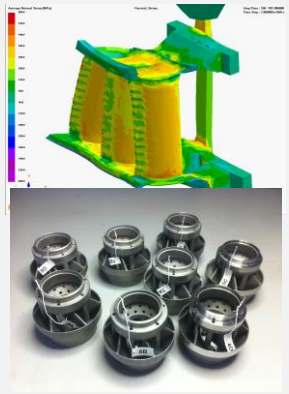


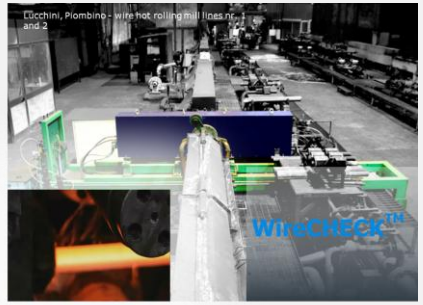


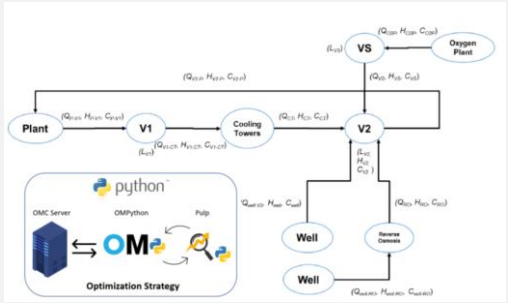
From Raw Material to Final Product











MATERIAL DEVELOPMENT

- Alloys Design for new materials at higher performance
- Alloy Design for Powders for Additive Manufacturing
- New special coatings

PROCESS DEVELOPMENT

- Steelmaking & Casting & Rolling & Forging
- Additive Manufacturing
- Heat treatment & Surface conditioning
- Combustion
- Welding and Joining

PRODUCT DEVELOPMENT

- Net shape and near net shape products
- Semi-products
- Coatings
- Flat, Long Products and Tubes
- Application Engineering
- Prototyping

CROSS – CUTTING TECHNOLOGIES

- Through process approach
- L2/L3 Control Systems
- Tailor made tools Customized sensors
- Technological DB

ENVIRONMENTAL SOLUTION

- Solid Waste Valorization
- Water Management
- Emission Reduction
- Energy Recovery

Hard-to-abate sectors

At around **1.9 billion tonnes** per year, **steel ranks second by volume** after cement. **However**, it **has the highest average CO_2 intensity**, driven primarily by the BF–BOF route.

Sector	Annual Production	Specific CO_2 emission t/t product	Source
Steel (BF)	1325 Mt	2.33	*worldsteel, World Steel in Figures 2025*
Steel (EAF)	548 Mt	0.68	worldsteel, *World Steel in Figures 2025*
Glass	> 150 Mt	1.0	*McKinsey, global data on glass*
Cement	4160 Mt	0.60	IEA, *Cement*: https://www.iea.org/reports/cement-3





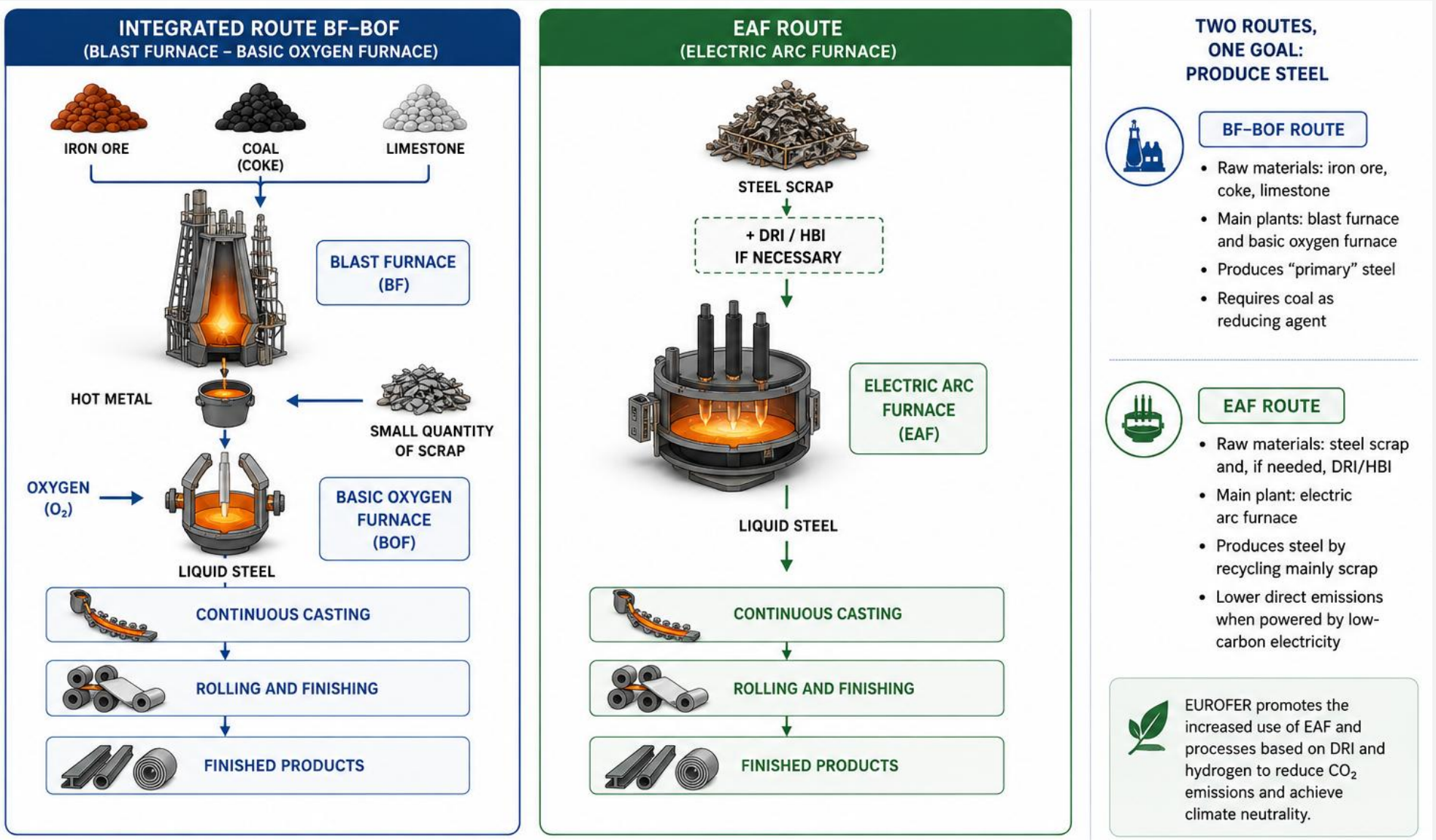




Decarbonization Strategies

Pathways / Groups	**Circular Economy** Enhancing the recycling of steel (i.e. scrap in BOF/EAF) and its by-products Resource efficiency (i.e. SPIRE)		
	Smart Carbon Usage (SCU) Process Integration with reduced use of carbon (+CCS)	Carbon Valorization/ Carbon Capture and Usage (CCU) (+CCS)	**Carbon Direct Avoidance (CDA)** Hydrogen Electricity
Description	Process Integration with reduced use of carbon	Using CO/CO_2 from steel mill as raw material (Chemical conversion of CO/CO_2)	Use of renewable electricity in basic steelmaking, i.e. production of H_2 to replace Carbon
Projects / Initiatives	Process Integration with reduced use of carbon	Steelanol, Carbon2Chem, FReSMe	HYBRIT, H2Future, SuSteel, GrInHy, MACOR/SALCOS, SIDERWIN

Decarbonization Strategies



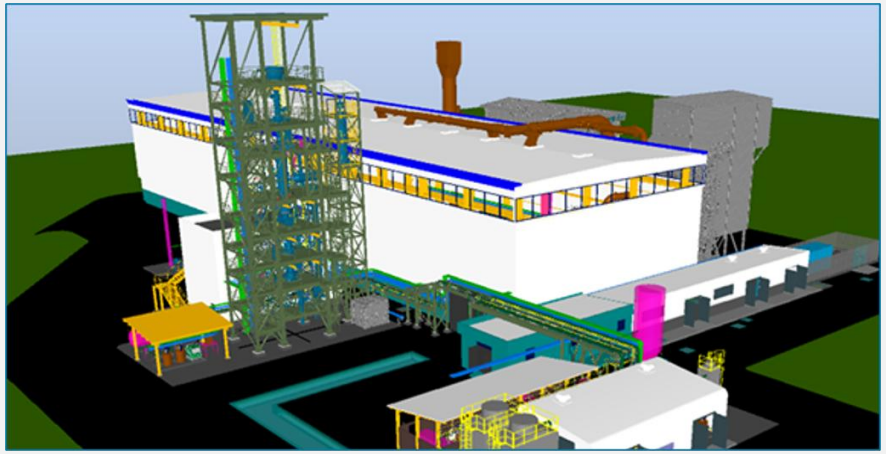
Steel production is expected to progressively **shift** from conventional routes **toward** Direct Reduction Processes (**DRP**) **coupled with** Electric Arc Furnaces (**EAF**), **or to scrap-based** production using **EAF** technology only.

The HYDRA Project

Funded by the European Union NextGenerationEU

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HYDRA is an “Important Projects of Common European Interest” (IPCEI) funded by the European Union in the framework of the NextGenerationEU, and is coordinated by **RINA** to decarbonize the steelmaking sector through **hydrogen**-related technologies.



HYDRA aims at developing an **industrial open platform** at Centro Sviluppo Materiali (CSM) headquarters in Castel Romano (Rome, Italy) **with pilot plants and labs** to **develop, qualify and validate** the use of **hydrogen in** every phase of **steel industry.**



The platform **will support** the decarbonization in the steelmaking processes **replacing the traditional route based on Blast Furnace**. The structure will consist of a direct iron ore reduction (DRI) plant using hydrogen as a reducing agent and an electric furnace.

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WP1: the study and development of methodologies for testing and qualification of materials and components to be used for the local transport of hydrogen;

WP2: the construction and development of the hydrogen-fed direct reduction pilot plant and process (DRP);

WP3: the construction and development of an EAF process metallurgy for DRI melting obtained with hydrogen;

WP4: the study and development of the 'downstream' use of hydrogen in reheating and heat treatment furnaces and its impact on steel quality



Direct Reduction Plant



Electric Arc Furnace

The HYDRA Project

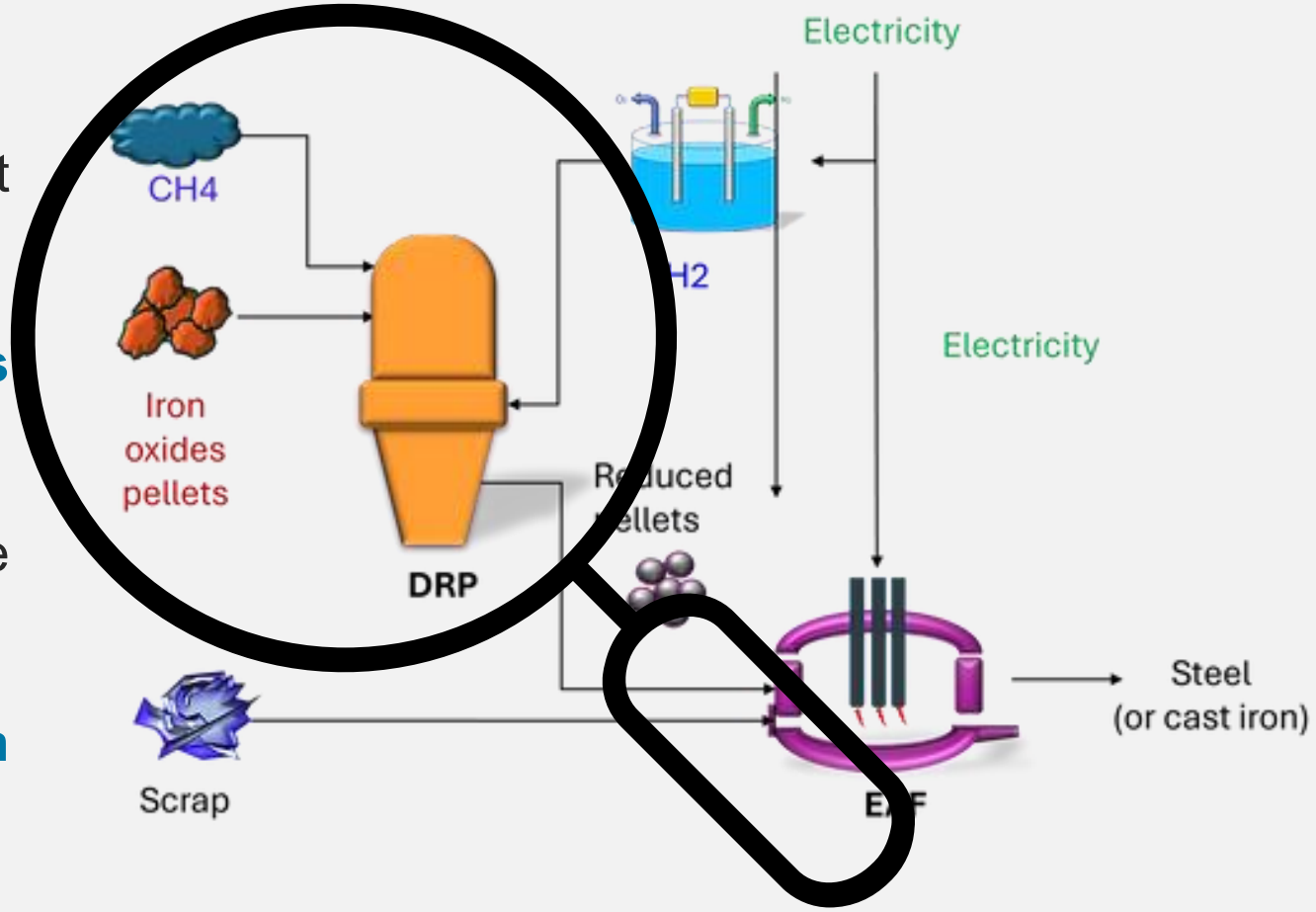
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The transition toward a hydrogen-based **steelmaking** won't be short and many technological aspects are still under discussion, but the main aim of the HYDRA project is facilitating this transition.

Several solutions will be investigated and tested:

- Use of many **mix CH_4-H_2** in both Direct Reduction plant and heating burners
- Investigation on **different raw materials grades** to produce DRI Direct Reduced Iron
- Mixing **DRI** and **Scrap** in different ratios in the melting furnace
- **Hydrogen** burning and **Secondary Carbon Carriers** injection in EAF



Direct Reduction: SoA

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Reduction of Iron Ore pathway with reducing gas:

$$Fe_2O_3 \rightarrow Fe_3O_4 \rightarrow FeO \rightarrow Fe$$

Natural Gas (CH_4) as reducing agent:

$$CH_4 + H_2O \rightarrow CO + 3H_2$$

$$3Fe_2O_3 + CO \rightarrow 2Fe_3O_4 + CO_2$$

$$Fe_3O_4 + CO \rightarrow 3FeO + CO_2$$

$$FeO + CO \rightarrow Fe + CO_2$$

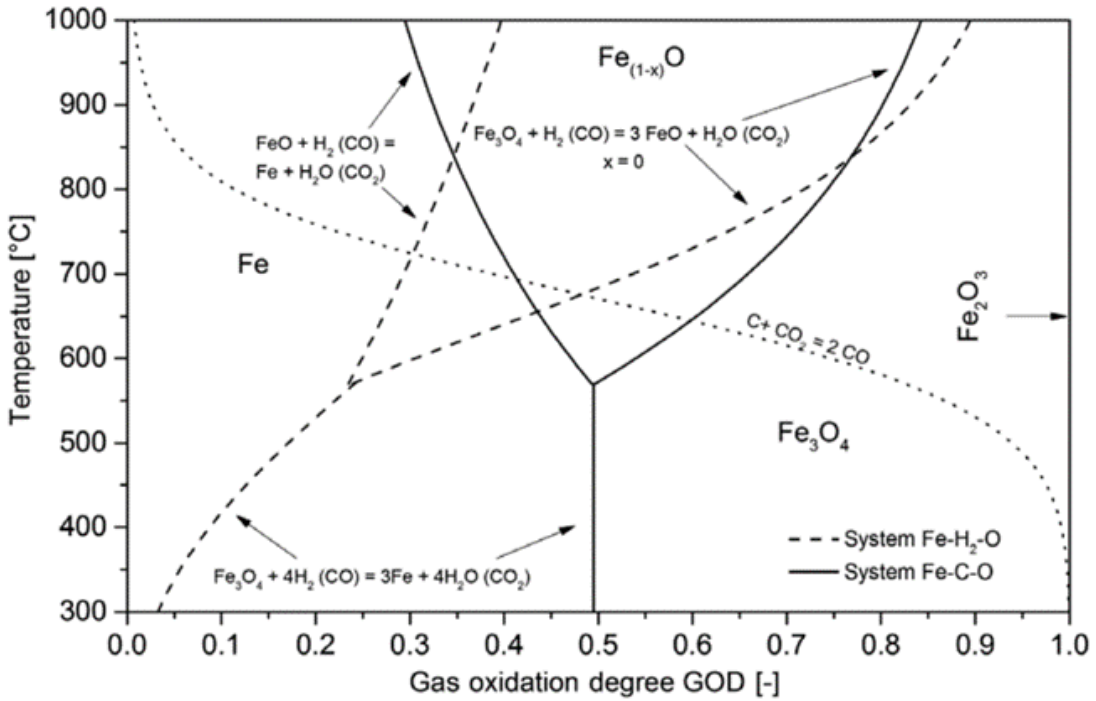
Hydrogen (H_2) as reducing agent:

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

$$(1\text{-}x)\ Fe_3O_4 + (1\text{-}4x)\ H_2 \rightarrow 3Fe_{(1-x)}O + (1\text{-}4x)\ H_2O$$

$$Fe_{(1-x)}\ O + H_2 \rightarrow (1\text{-}x)\ Fe + H_2O$$

Process Termodynamics



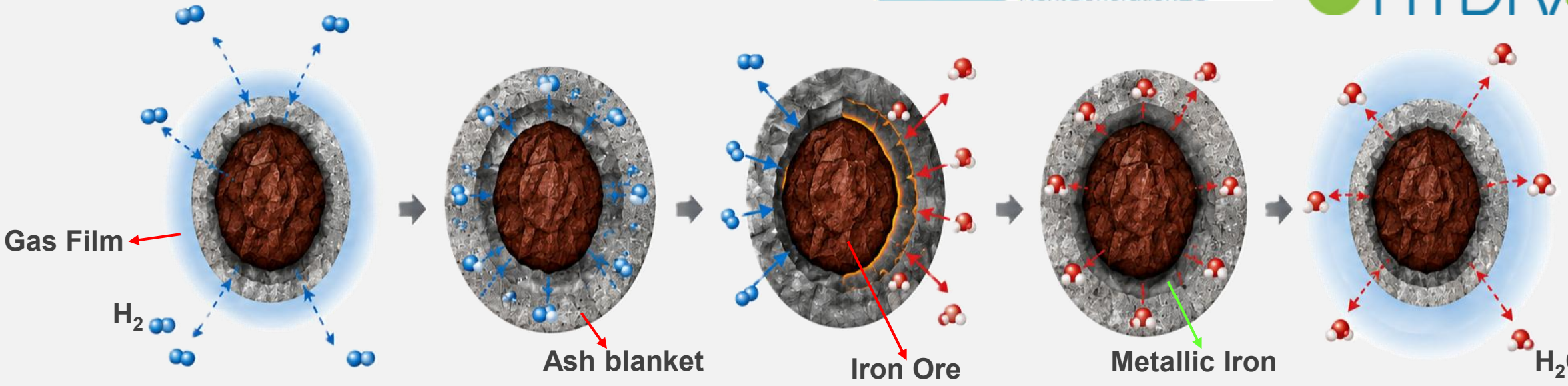
Baur-Glässner diagram for the Fe-O-H_2 and Fe-O-C systems including the Boudouard equilibrium at 1 bar with pure carbon.

The reduction reaction with Hydrogen is endothermic

Direct Reduction: SoA

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Five steps can be considered **for iron ore reduction by hydrogen**:

1. **Diffusion** of **hydrogen** ( ) **through** the **gas film** ( )surrounding the iron ore particle.
2. **Diffusion** of **hydrogen through** the **blanket of ash** ( ) (consisting of the final product, i.e., iron, and gangue such as silica, alumina, etc.) **to** the **surface of** the **unreacted iron ore**.
3. **Chemical reaction** of hydrogen **with iron ore** ( ) at this reaction surface.
4. **Diffusion** of **H_2O** (gaseous product) **through the ash** back **to the exterior** surface of the particle.
5. **Diffusion** of **H_2O** (gaseous product) **through the gas film** back to the main body of fluid.

Low Grade Pellets

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Low Grade Pellets (LG)



Chemical Component	
Fe_{tot}	64.3
Fe_{met}	<0.5
Fe^{+2}	<0.5
Fe^{+3}	~63.0

Chemical Component (%)	
C	<0.1
S	<0.05
N	0
O	13.2
P_2O_5	<0.05
SiO_2	4.97
Al_2O_3	0.64
CaO	0.77
MnO	0.08
MgO	1.04
Na_2O	0.4
K_2O	0.06





H_2 Flow rate (Nl/h)	50	120	200
Time (min)			
20	800/1000 °C	800/1000 °C	800/1000 °C
40	800/1000 °C	800/1000 °C	800/1000 °C
60	800/1000 °C	800/1000 °C	800/1000 °C
90	800/1000 °C	800/1000 °C	800/1000 °C

LG Weight Loss

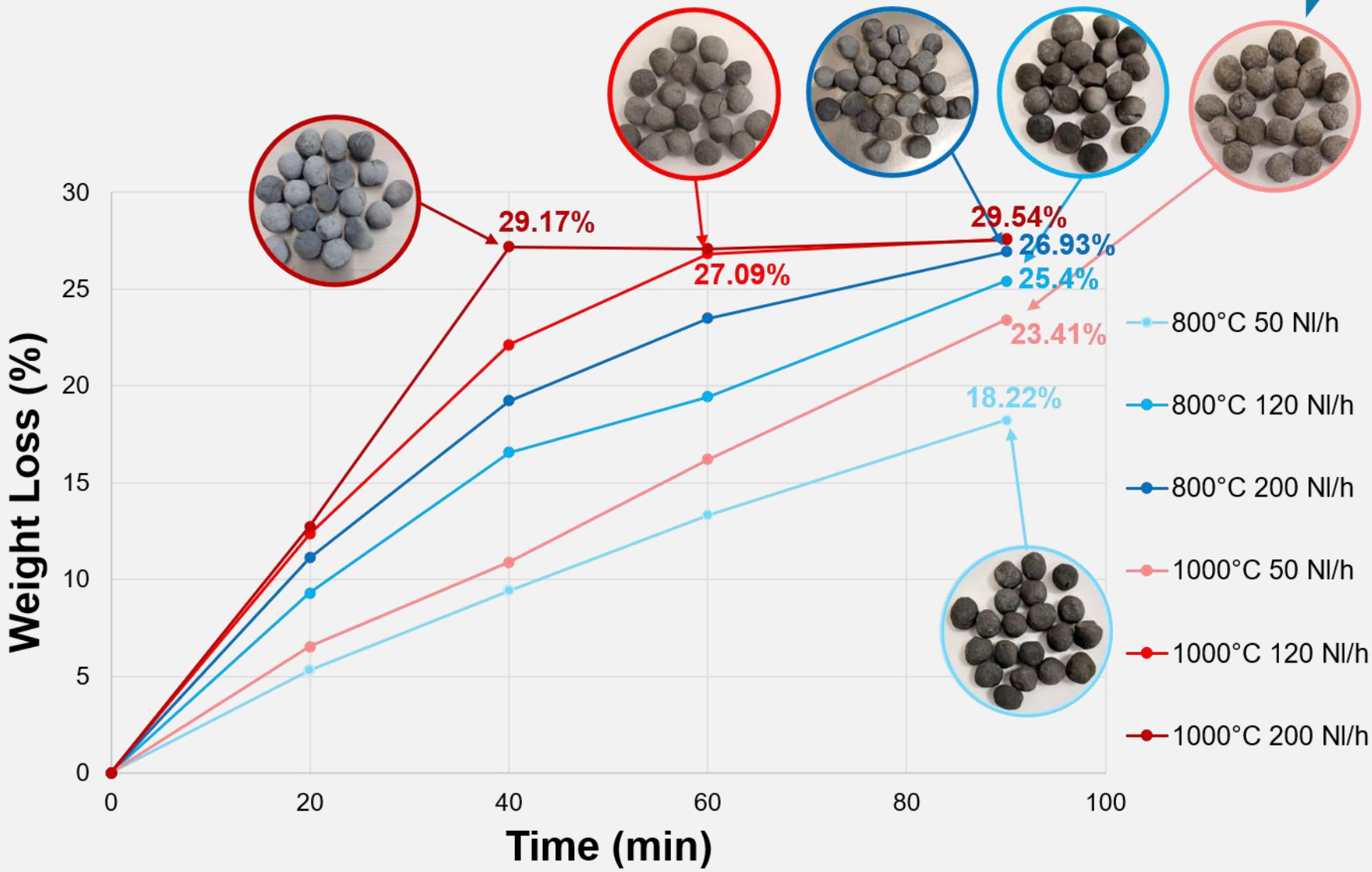
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Statistical Analysis (ANOVA)

Strong dependency of reduction kinetic on all operating parameters with hydrogen flow rate and residence time playing the most significant role.

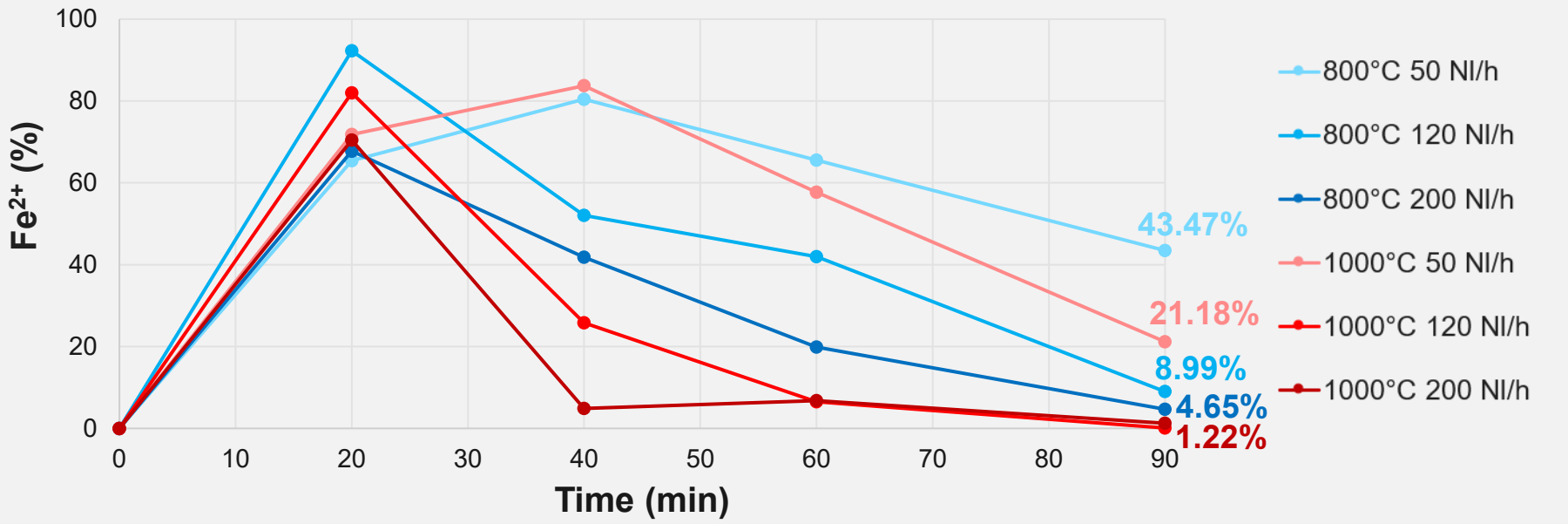
This outcome is extremely interesting from the pilot scale perspective. Indeed, HYDRA shaft furnace is designed to work with an almost fixed operating temperature, but the results allow to infer that iron ore pellets reduction can be optimized and tailored just modifying residence time and hydrogen flowrate.

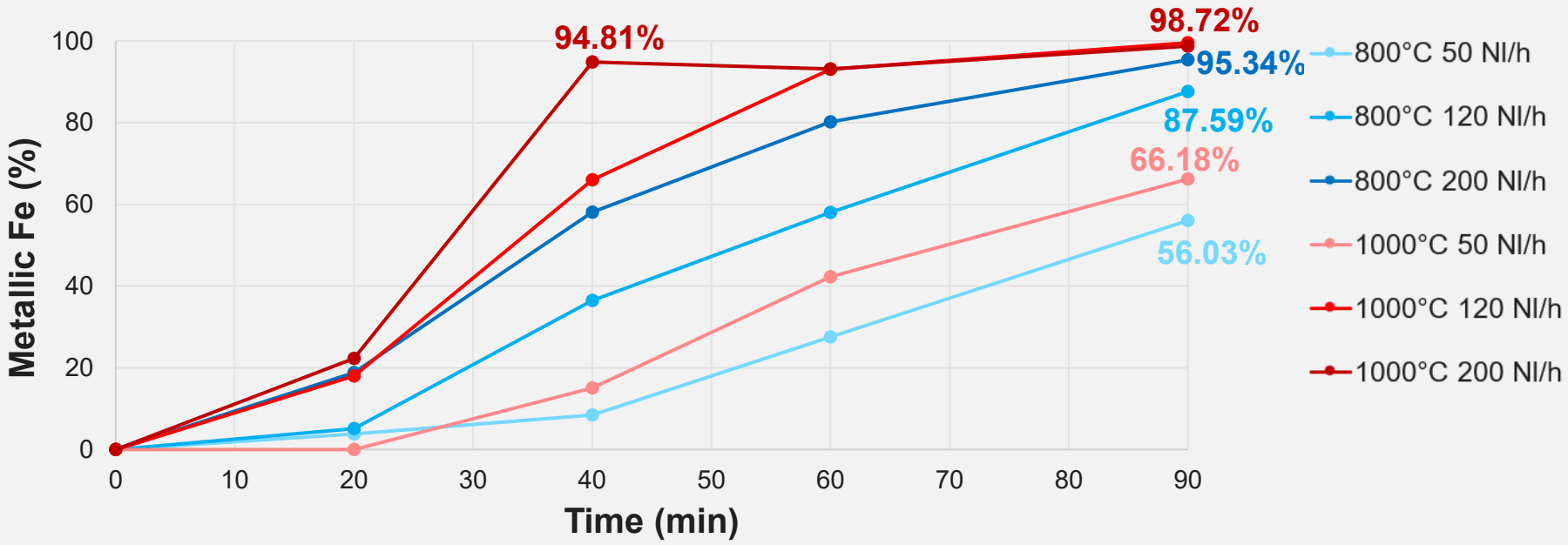


LG Iron Speciation

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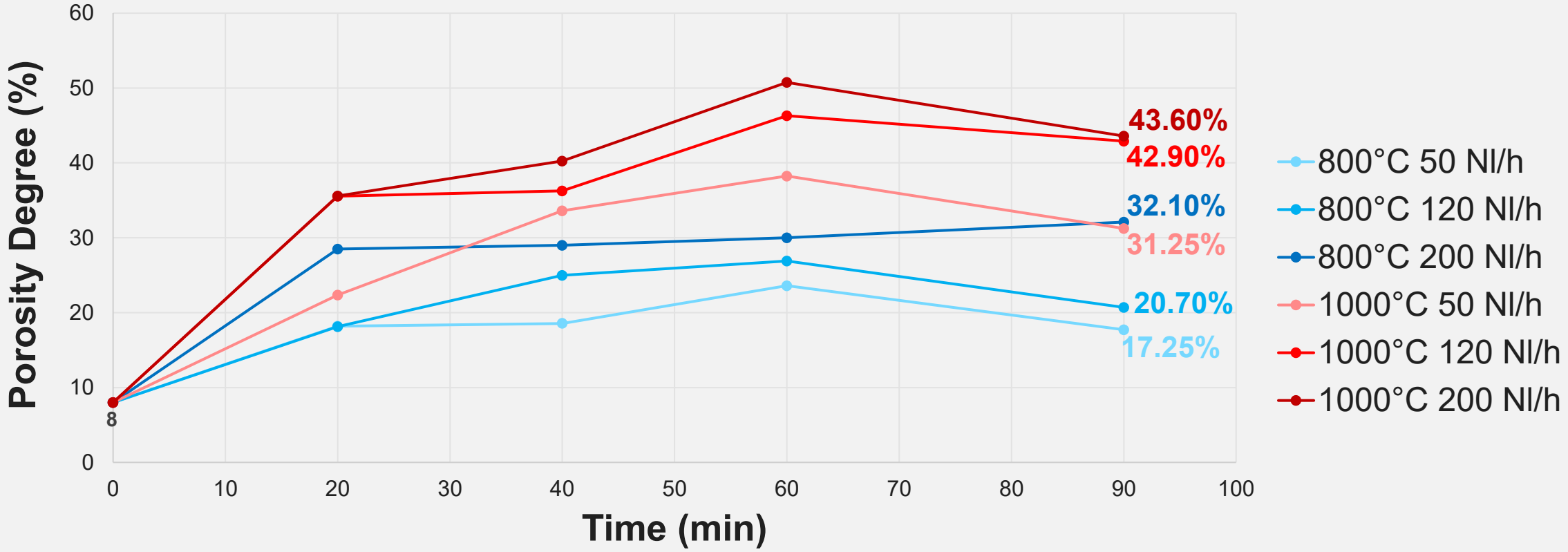
Iron Speciation Results

Hydrogen flow rate strongly controls the reduction kinetics: 120 and 200 Nl/h enable rapid Fe^{3+} conversion and near-complete metallization, whereas 50 Nl/h results in significant residual Fe^{2+} and incomplete metallization, even after 90 minutes.

The **best performance** is achieved at **1000°C** and **200 Nl/h**, reaching **94.81% metallization**, **after** only **40 minutes**.

LG Porosity

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Pellet mass loss is accompanied by **increased porosity**, which **promotes reduction** by **expanding** the **specific surface area** and **improving contact with hydrogen**. The porosity decrease observed after prolonged treatment is likely caused by surface diffusion and pellet contraction.

*The image-based measurements should be considered qualitative rather than absolute.

High Grade Pellets

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High Grade Pellets (HG)



Chemical Component (%)	
P_2O_5	0.15
SiO_2	**1.71**
Al_2O_3	0.5
CaO	1.14
MnO	0.1
MgO	0.42
Na_2O	<0.1
TiO_2	0.05

Chemical Component	
Fe_{tot}	**67**
Fe_{met}	-
Fe^{+2}	0.1
Fe^{+3}	66.9



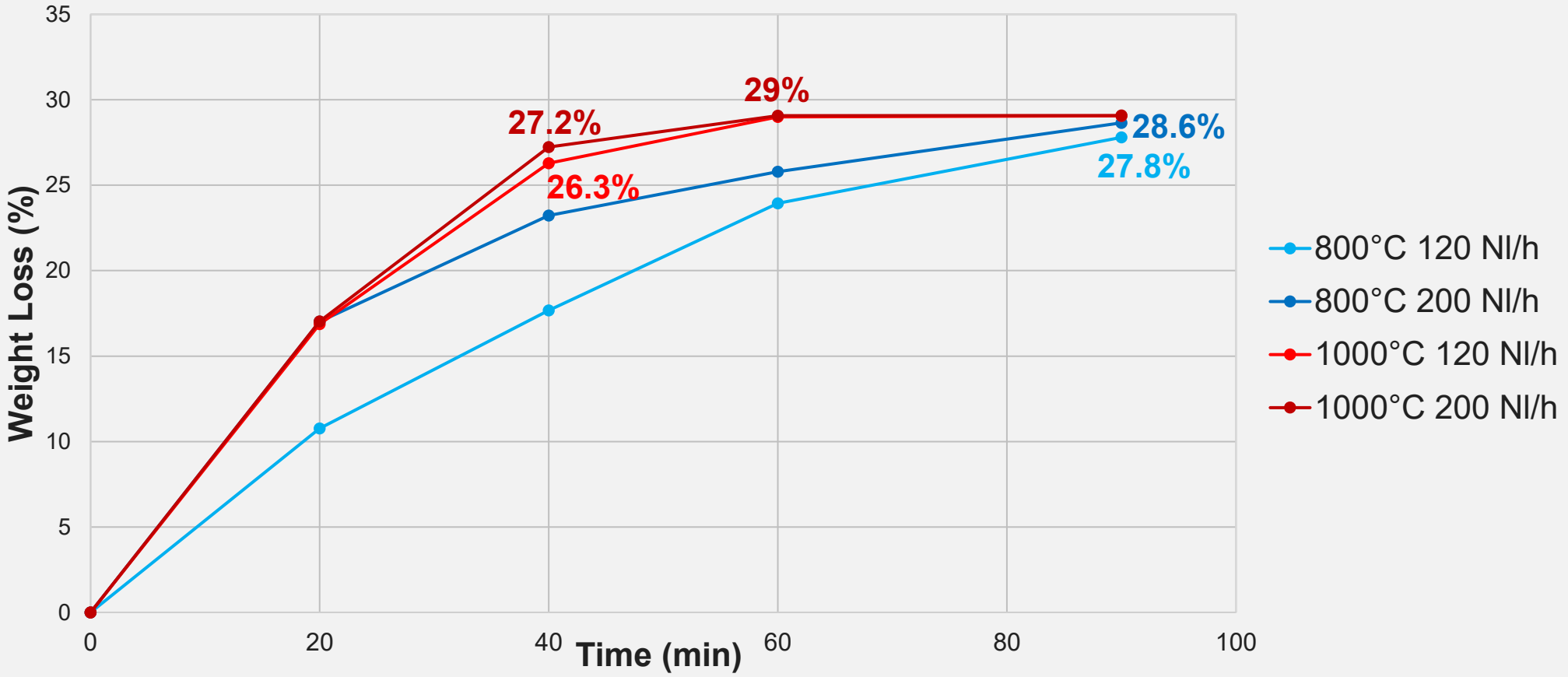


H_2 Flow rate (Nl/h)	120	200
Time (min)		
20	800/1000 °C	800/1000 °C
40	800/1000 °C	800/1000 °C
60	800/1000 °C	800/1000 °C
90	800/1000 °C	800/1000 °C

HG Weight Loss

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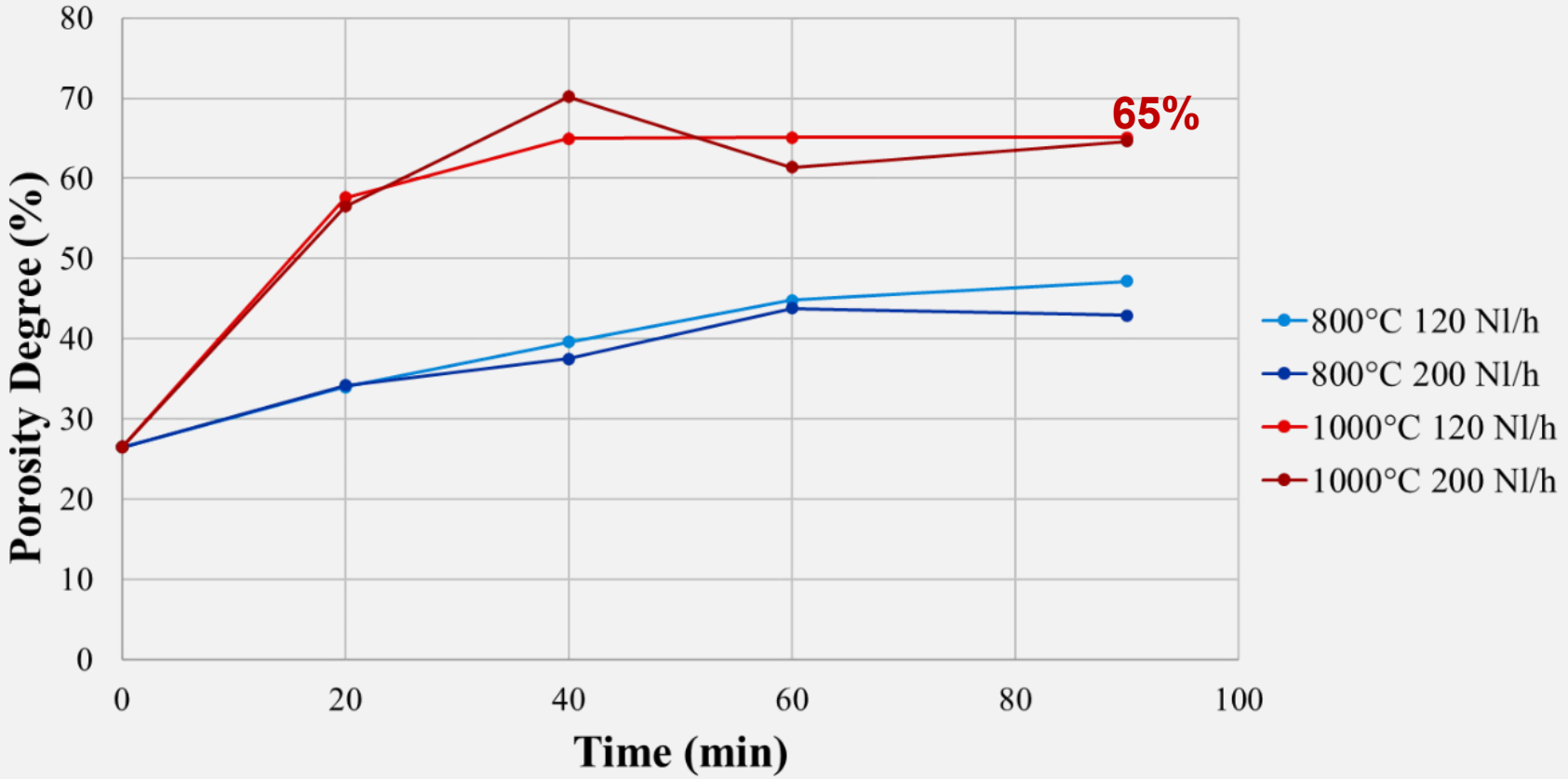


With **HG pellets**, the **weight loss** trends point out there are **no significant differences in pellets reduction behavior at 1000 °C for the two** different **flowrates** of **120** and **200** Nl/h which report a mass loss of **26.3** and **27.2 %** after **40 minutes** and of **29 % after 60 minutes**, respectively. Comparable results can be achieved at **800 °C only** after **90 minutes** with a mass loss of **27.8%** with **120 Nl/h** and of **28.6 %** with **200 Nl/h**.

HG Porosity

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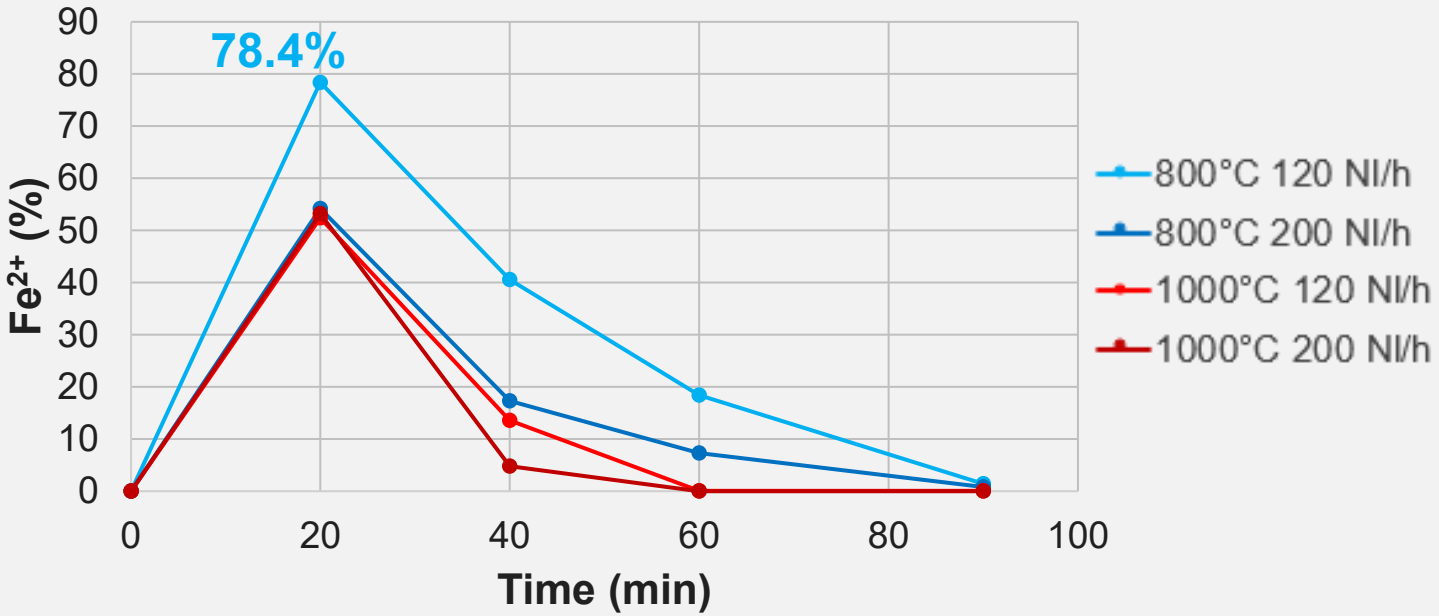
HG pellets mass loss is accompanied by a **progressive increase** in pellets **porosity** as already reported for LG pellets

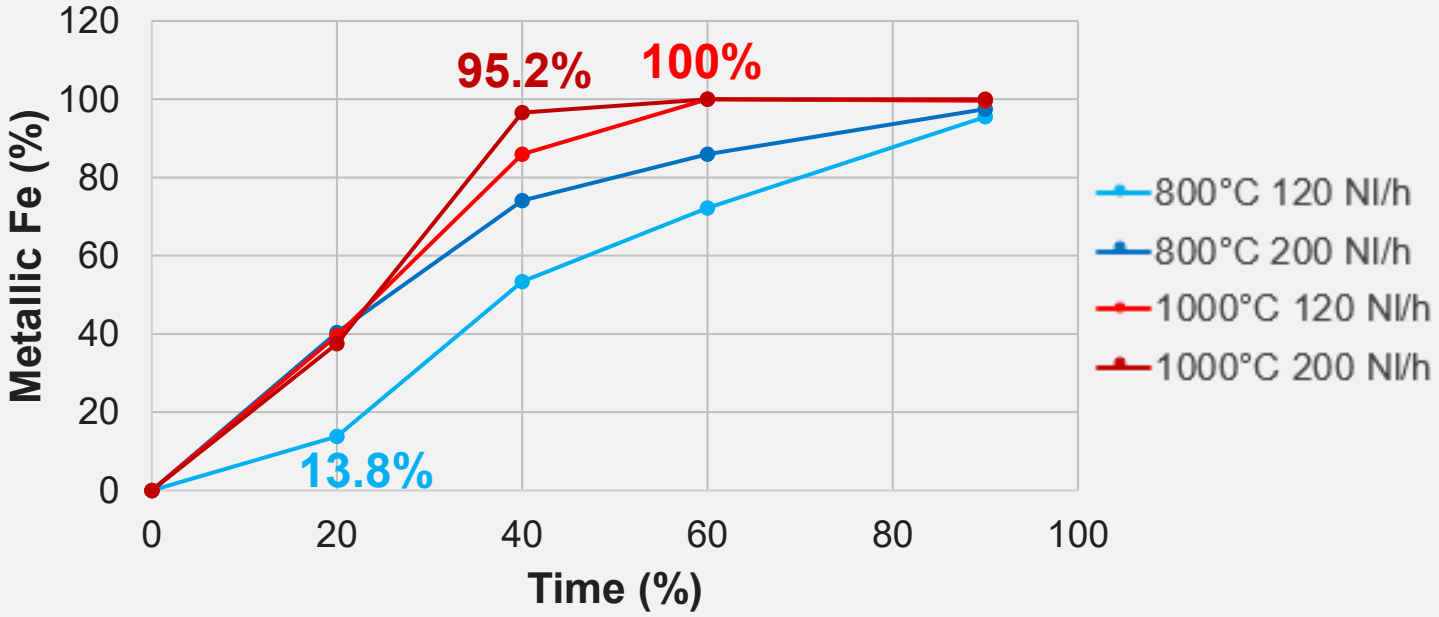
Higher porosity values are achieved **with HG** pellets **compared to LG** ones. In particular, **HG** pellets achieve an **average porosity of 65 % at 1000 °C** for **both hydrogen flow rates whereas** values around **50** and **45 %** are obtained **with LG** pellets at 1000 °C and with hydrogen flowrates of **200** and **120 Nl/h**, respectively. This is **coherent with** the **inherent higher gangue content of LG pellets** which intrinsically **decreases** the **amount of reducible iron.**

HG Iron Speciation

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As observed for LG pellets, **Fe^{3+}** is **almost fully converted** into **Fe^{2+}** after **20 minutes**; however, at **800 °C** and **120 Nl/h**, the **higher residual Fe^{2+}** content (**78.4%**) reflects a **lower initial metallization** degree of **13.8%**, compared with **37.5–40%** for the **other configurations**. **Full metallization** is **reached** after **90 minutes** at **800 °C** (95.5–97.5%), while **at 1000 °C** the process is **faster**, requiring **60 minutes at 120 Nl/h** and only **40 minutes at 200 Nl/h to achieve 95.2% metallization**.

Conclusion

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- **Reduction kinetics** are strongly **dependent on** operating **temperature**, **hydrogen flow rate**, and **residence time**, with temperature and residence time being universally influential parameters for both LG and HG pellets.

- For **low-grade pellets**, **hydrogen flow rate plays a crucial role** due to mass transfer limitations. **Low flow rates** (50 Nl/h) lead to significantly **reduced metallization degrees**, while **higher flow rates** (120–200 Nl/h) enable **near-complete reduction** within reasonable timeframes.

- **High-grade pellets exhibit superior reducibility**, achieving **higher metallization degrees** and porosity values **under all tested conditions**. For these materials, **differences between 120 and 200 Nl/h** become **negligible**, indicating that above a certain threshold the process is not limited by hydrogen supply.

- **Increasing** the **temperature from 800 to 1000 °C accelerates reduction** and significantly **shortens the residence time required** for full metallization.

- **Process efficiency** can be **optimized** by **tailoring hydrogen flow rate** and **residence time** to pellet characteristics, while **avoiding prolonged treatments** that may cause densification and reduce porosity.

Next Steps

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- **Commission** the **DRP pilot plant** and **validate DRI production** using both **100% methane and 100% hydrogen**, supporting process optimization and scale-up
- **Install and commission the new MM6000 testing furnace**, significantly expanding the laboratory-scale experimental capabilities for iron ore reduction.
- Investigate reduction under **tailored mixtures of H_2, CH_4, N_2, CO, and CO_2**, reproducing a wide range of process conditions.
- Use the **MM6000** to assess the influence of **gas composition**, **temperature**, **flow rate**, and **residence time** on reduction kinetics, metallization, and pellet properties.
- Use **MM6000 for extensive laboratory campaigns** to identify the most promising operating conditions and raw materials **before validation at pilot scale**.



MM6000 test furnace



Thanks for Listening

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https://www.hydra-project-ipcei.eu/
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Our experience. Your growth.

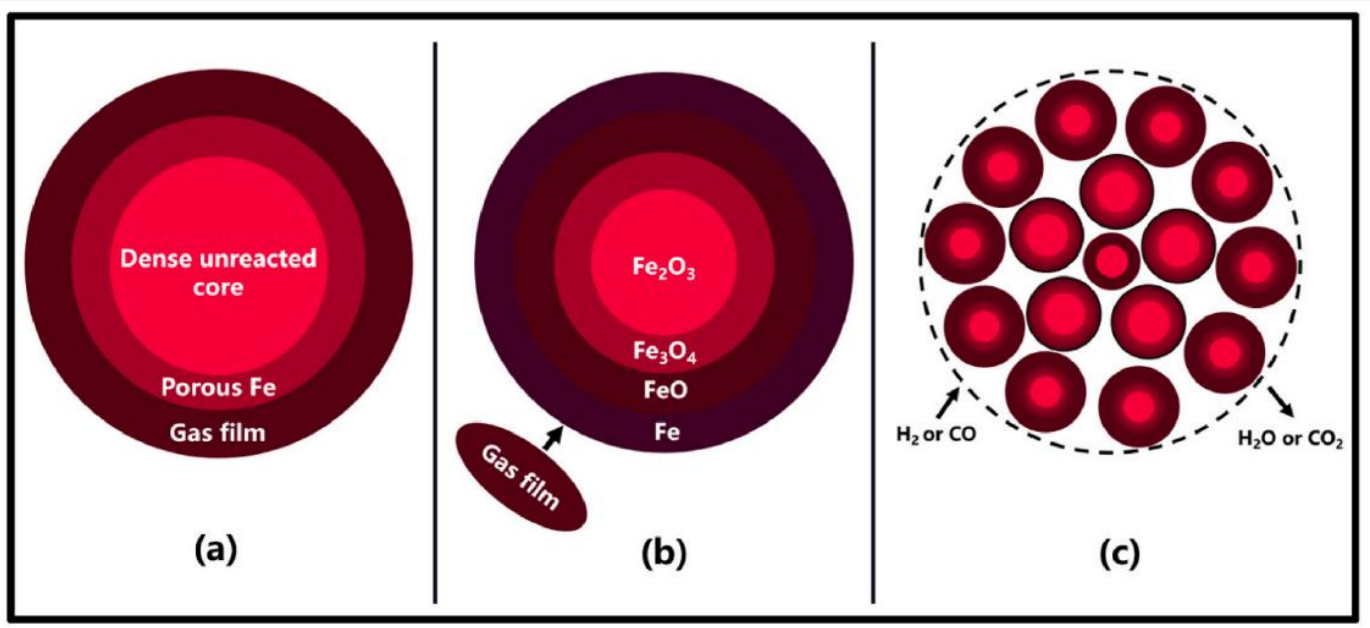


Supporting Information

Direct Reduction: SoA

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a) Single-interface shrinking core model

The **pellet** is represented as a dense structure consisting of an unreacted iron oxide core surrounded by an iron layer and an external gas film. The **reducing gas diffuses through the gas film** and the iron layer to **reach the reaction interface**, while the **gaseous products diffuse outward into the bulk** gas phase.

b) Three-interface shrinking core model

The reduction proceeds through **three moving reaction interfaces** corresponding to the transformations **hematite–magnetite, magnetite–wüstite, and wüstite–iron**. **Gas behavior** is treated under **pseudo-steady-state conditions**, assuming an **instantaneous balance** between **material transport and reactant consumption** at each advancing interface.

c) Porous solid model

The **pellet** is modeled as an **assembly of uniformly sized porous particles** whose overall physical structure remains unchanged during reduction. Each **particle follows a shrinking-core mechanism**, while the **reducing gas penetrates the porous solid** and **reactions occur across the particle surfaces**; this approach is widely used in CFD simulations.

Iron Speciation

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1. Total Iron Determination (FeTOT)

- The sample is completely dissolved using a mixture of **hydrochloric acid (HCl)** and **hydrofluoric acid (HF)**.
- Any ferric iron (**Fe^{3+}**) present in solution is reduced to ferrous iron (**Fe^{2+}**) using **stannous chloride ($SnCl_2$)**.
- Excess reducing agent is neutralized before titration.
- Total iron is determined by titration with standardized **potassium dichromate ($K_2Cr_2O_7$)**.

Main reaction:

$$6Fe^{2+} + Cr_2O_7^{2-} + 14H^+ \rightarrow 6Fe^{3+} + 2Cr^{3+} + 7H_2O$$

2. Ferrous Iron Determination (Fe^{2+})

- The sample is dissolved under controlled conditions to prevent oxidation of Fe^{2+} during digestion.
- Ferrous iron is directly titrated with a standardized oxidizing solution, typically **potassium dichromate**.

Reaction with dichromate:

$$6Fe^{2+} + Cr_2O_7^{2-} + 14H^+ \rightarrow 6Fe^{3+} + 2Cr^{3+} + 7H_2O$$

3. Metallic Iron Determination (Fe^0)

- Metallic iron is selectively dissolved using an acidic medium while minimizing attack on iron oxides.
- During dissolution, metallic iron is oxidized and hydrogen gas is evolved.

Reaction:

$$Fe^0 + 2H^+ \rightarrow Fe^{2+} + H_2 \uparrow$$

4. Ferric Iron Determination (Fe^{3+})

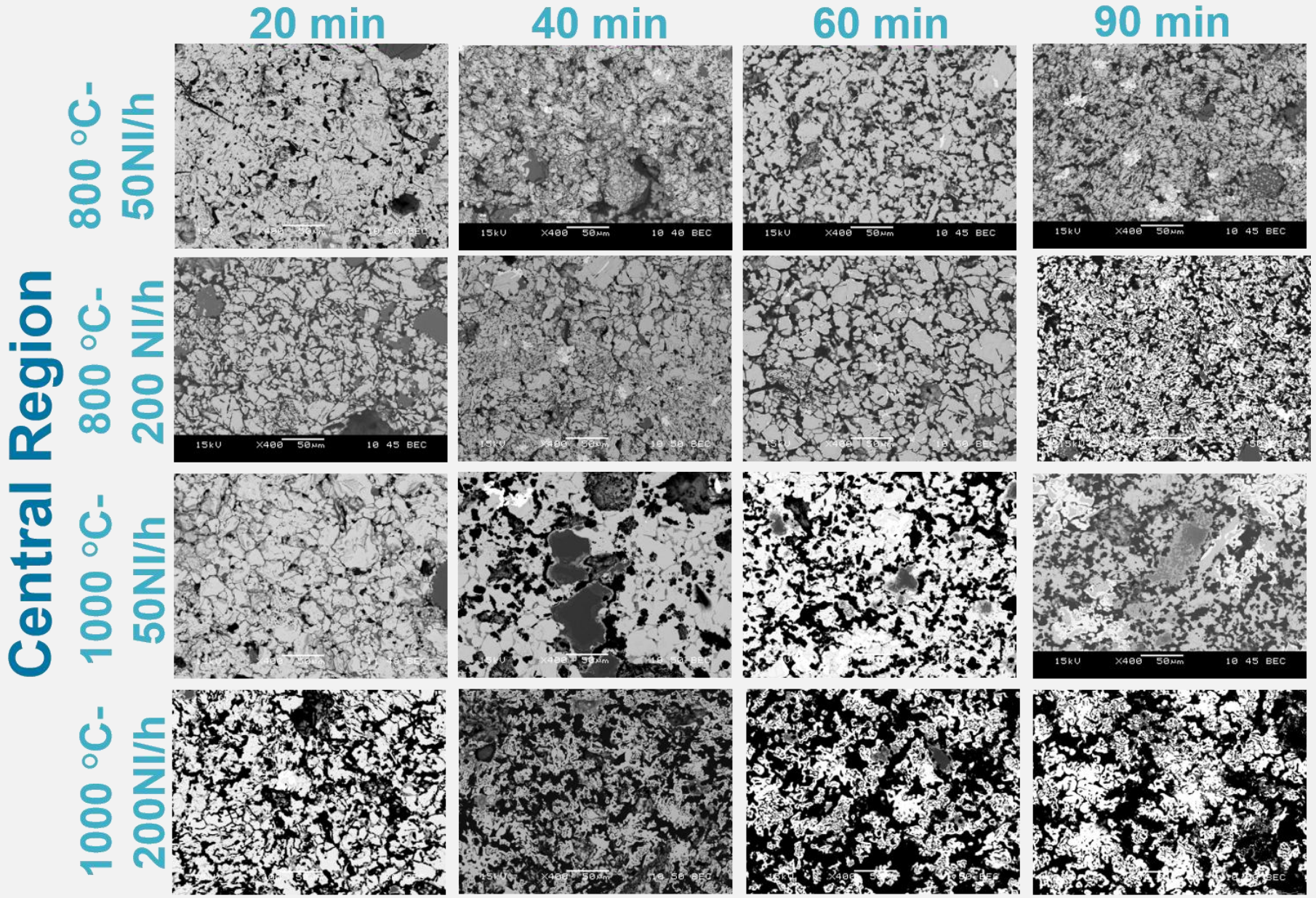
- Ferric iron is not measured directly.
- Its concentration is calculated by mass balance:

$$Fe^{3+} = Fe_{TOT} - Fe^{2+} - Fe^0$$

LG Porosity

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HG Porosity

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