



Development of new methodologies **S** for In**D**ustrial
CO₂-fre**E** steel p**R**oduction by electro**WIN**ning

SIDERWIN: A breakthrough technology to decarbonize
primary steel production through direct electrification

Webinar March 23rd 2023

*This project has received funding from the European
Union's Horizon 2020 research and innovation
programme under grant agreement No 768788*



www.siderwin-spire.eu



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WELCOME AND INTRODUCTION

José Ignacio Barbero - TECNALIA
Webinar March 23rd 2023



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WELCOME AND INTRODUCTION

José Ignacio Barbero - TECNALIA
Webinar March 23rd 2023

The background image shows a modern office interior with large glass windows. Several people are silhouetted against a bright sunset or sunrise, creating a warm, golden glow. The people are standing and talking, and their reflections are visible on the polished floor. The overall atmosphere is professional and welcoming.

Welcome

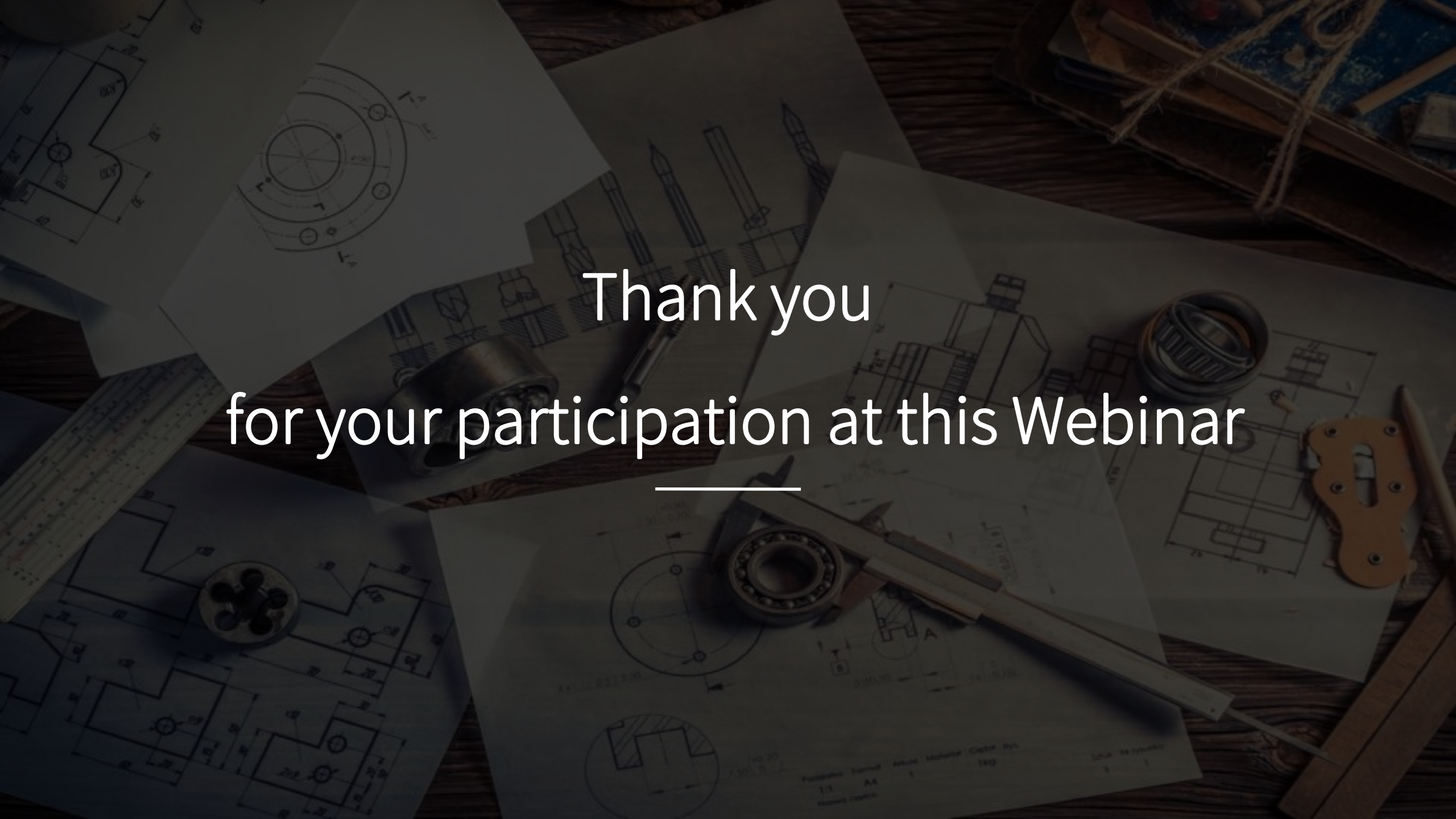
AGENDA

Time	Topic	Speaker
15.00-15.10	Welcome and introduction to the Webinar.	José Ignacio Barbero (TECNALIA)
15.10-15.20	SIDERWIN Project General Overview.	Valentine Weber-Zollinger (ArcelorMittal)
15.20-15.35	The decarbonization strategy of ArcelorMittal – how and why is iron electrowinning a promising for the future of steel?	Jean-Paul Allemand (ArcelorMittal)
15.35-15.45	Iron Electrowining – Lessons learned.	Daniela V. Lopes (Uni. Aveiro)
15.45-15.55	Alternative feeding materials. Current status and future perspectives.	Dimitrios Panias (NTUA)
15.55-16.15	Iron production by electrolysis at pilot scale.	Thierry Conte (CFD Numerics) Salah Touhami (ArcelorMittal)
16.15-16.30	The flexible potential of SIDERWIN process for the future European power system.	Morgan Barberousse (EDF)
16.30-16.50	What is the environmental impact and cost of steel decarbonization with SIDERWIN?	Roland Kahmann (RECOY)
16.50-17.00	Conclusions and Perspectives.	Valentine Weber-Zollinger (ArcelorMittal)
17.00-17.15	Questions & Answers (Final Round).	José Ignacio Barbero (TECNALIA)

WELCOME

- INSTRUCTIONS

- The webinar will be recorded and available in the web later. You will receive a link.
- The attendees have the microphone muted. But you can communicate through the chat.
- After each presentation there will be some time for questions. Please write your questions in the chat.
- At the end of the webinar there will be time for questions.

The background is a dark, artistic composition of technical drawings and mechanical parts. It includes various engineering sketches such as cross-sections, orthographic projections, and circular diagrams with dimension lines. Scattered among the papers are physical components: a ball bearing, a small metal flange, a pencil, and a ruler. The overall aesthetic is professional and engineering-oriented.

Thank you
for your participation at this Webinar



Development of new methodologies for Industrial
CO₂-free steel production by electro-winning

SIDERWIN Project General Overview

Valentine Weber-Zollinger – Coordinator ArcelorMittal
Webinar March 23rd 2023

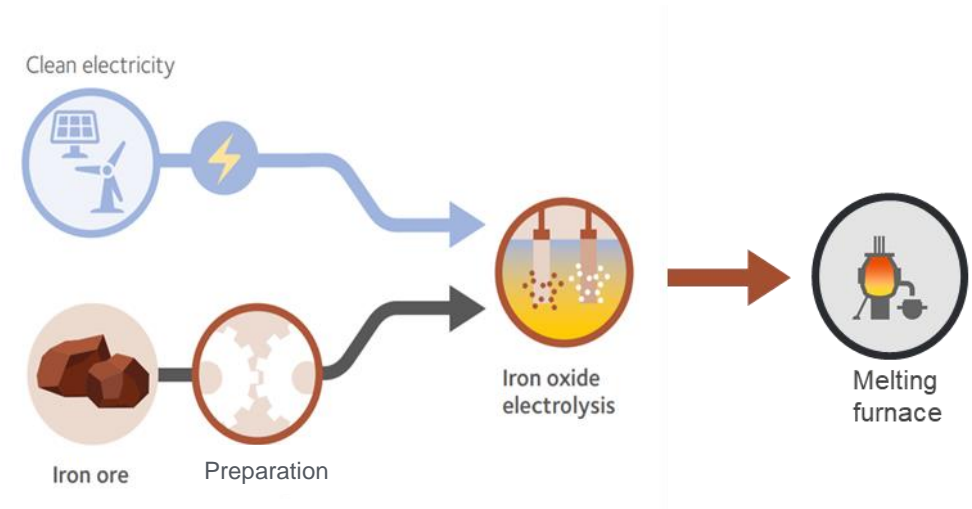
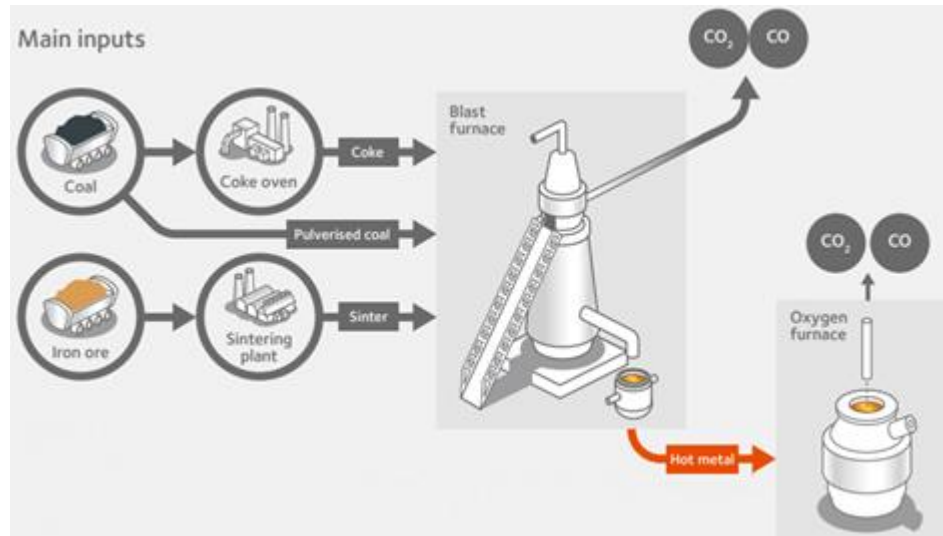
Development of new methodologies for Industrial CO₂-free steel production by electroWinning

To develop an innovative electrochemical process to transform iron oxide into steel metal plates

To produce steel by electrolysis without direct CO₂ emissions

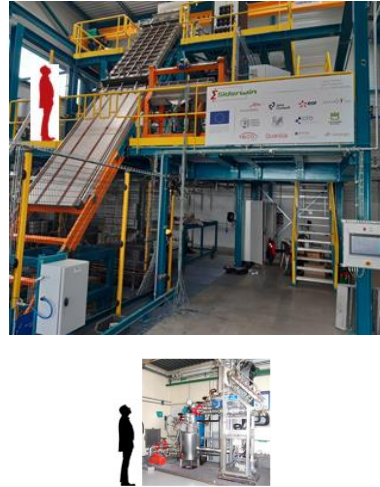
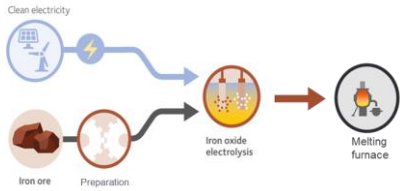


<https://www.siderwin-spire.eu>



A breakthrough compared to the conventional steelmaking route by iron electrowinning at low temperature in an aqueous based electrolyte.

Objectives of the project



Development of
an
electrochemical
route for primary
steel production

Industrially
feasible new
processsing
route

Raw material
efficiency during
steel production

Iron metal
production from
Renewable
Energy Sources

Close to market
research

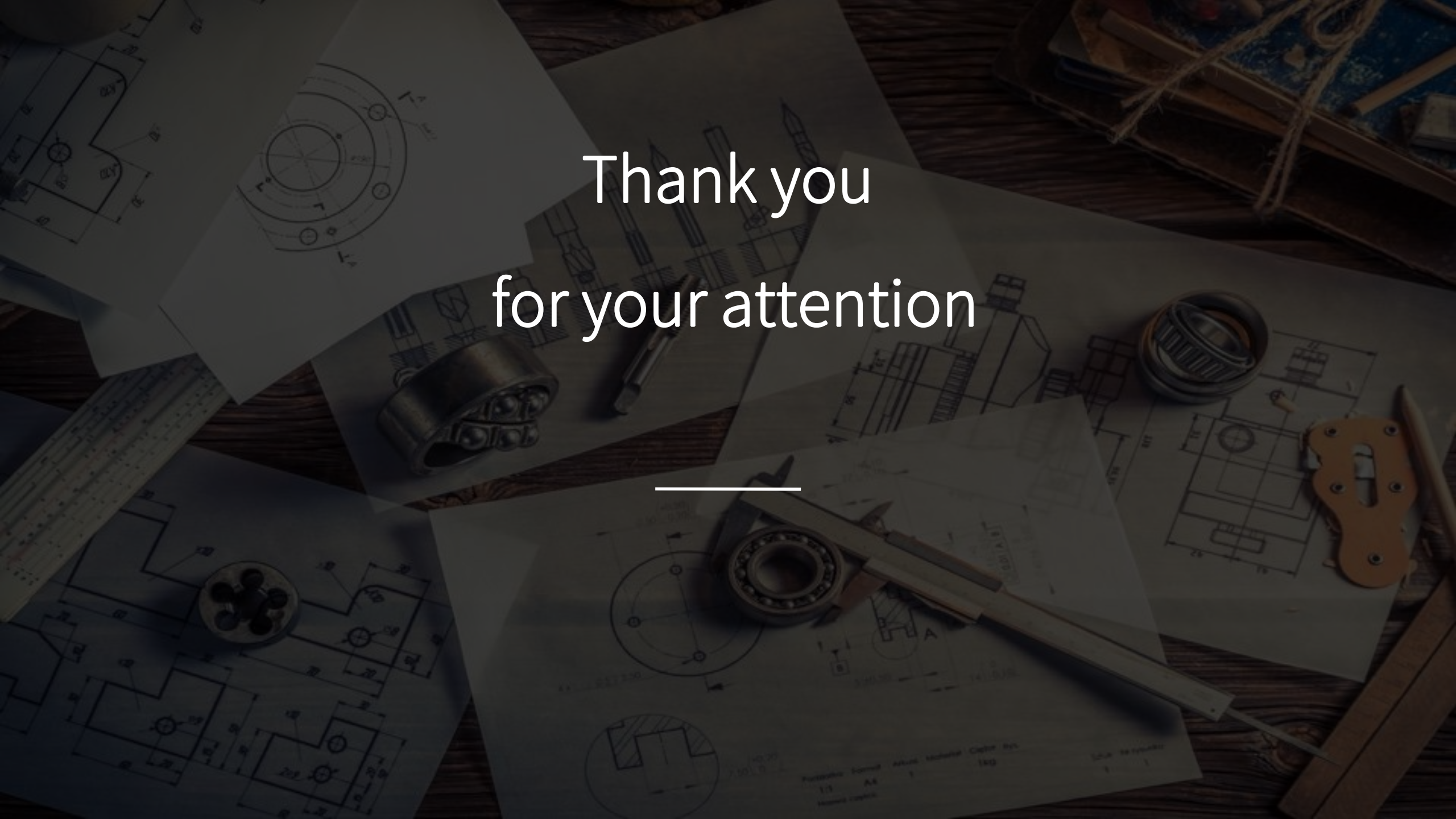
- 5 years project 2017-2023.
- Budget: 6.8 M€ including 2 M€ for the pilot.
- 12 partners: 4 Companies + 4 SMEs + 4 RTO.
- 7 different countries.
- Multisectoral:
steel, non-ferrous and power.
- Coordinated by ArcelorMittal.



ΣIDERWIN project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 768788.



This study reflects only the author's views, and the Commission is not responsible for any use that may be made of the information contained therein.

The background is a collage of technical drawings and mechanical components. It includes various blueprints with geometric shapes, circles, and lines. There are also images of mechanical parts like a bearing, a small motor or actuator, and a metal bracket. A wooden ruler and a pencil are visible in the bottom right corner. The entire image has a dark, semi-transparent overlay.

Thank you
for your attention



Development of new methodologies for Industrial
CO₂-free steel production by electrowinning

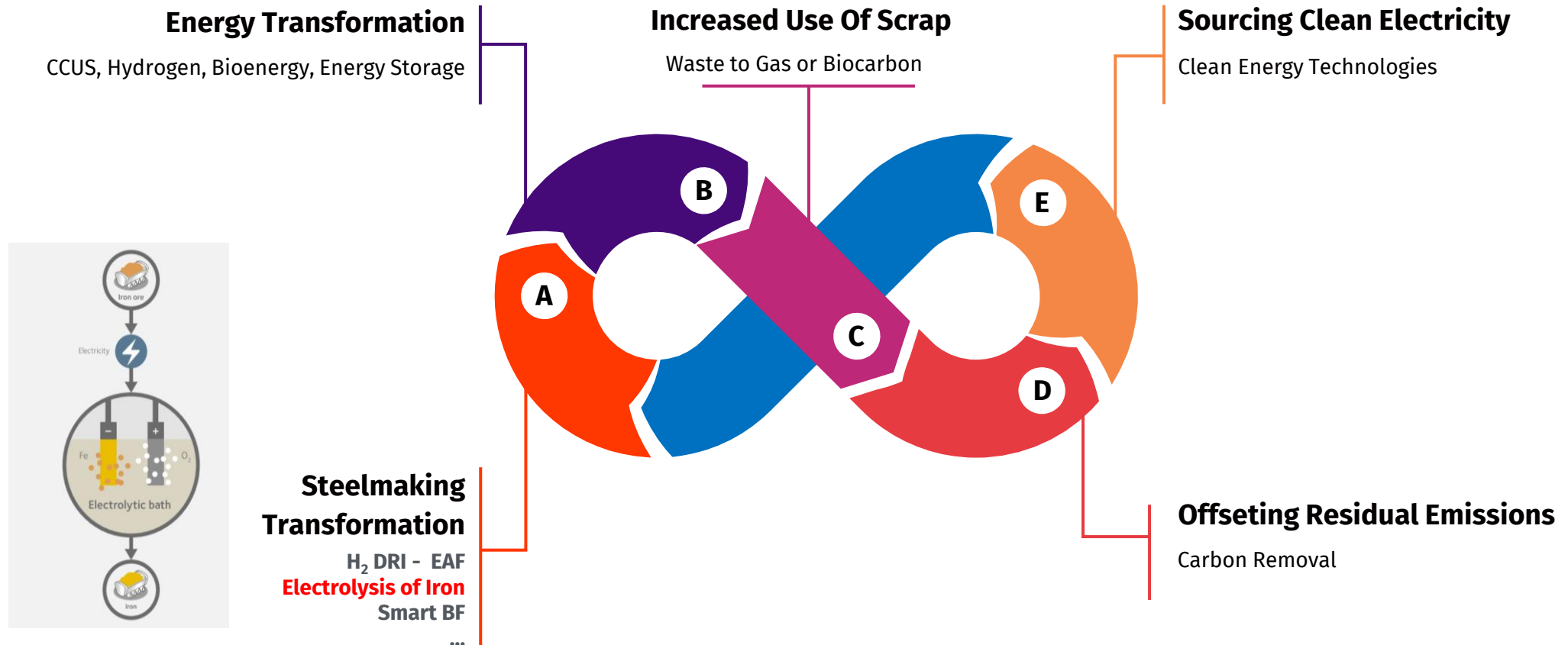
The decarbonization strategy of ArcelorMittal – How and why is
iron electrowinning a promising for the future of steel?

Jean-Paul Allemand – ArcelorMittal
Webinar March 23rd 2023

ArcelorMittal has adopted an ambitious set of carbon targets that will lead our sector in reaching net-zero by 2050



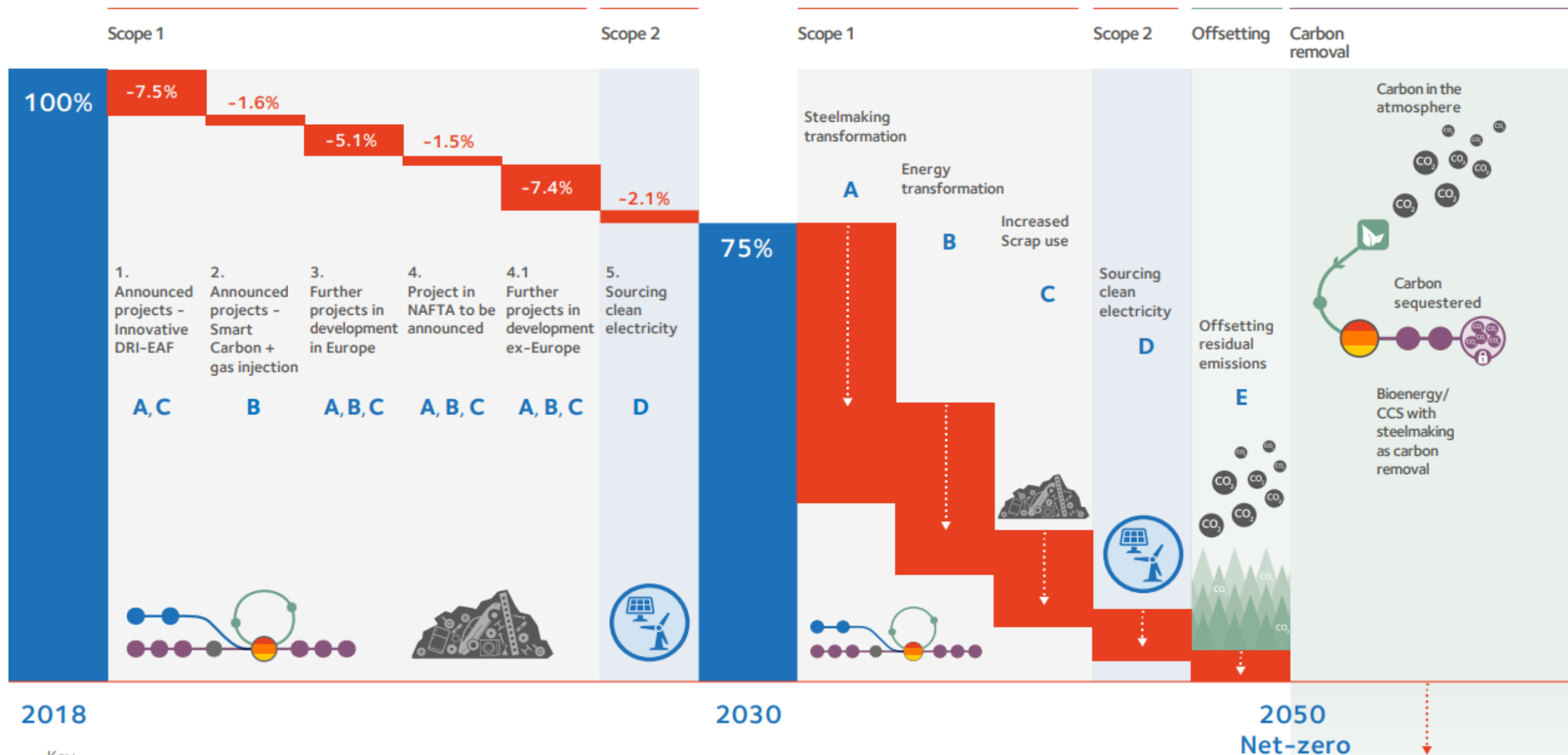
ArcelorMittal decarbonisation strategy - Net-Zero Roadmap



Our roadmap features five groupings of actions and initiatives that act as stepping stones to achieving carbon-neutrality by 2050.




ArcelorMittal CO₂ Roadmap



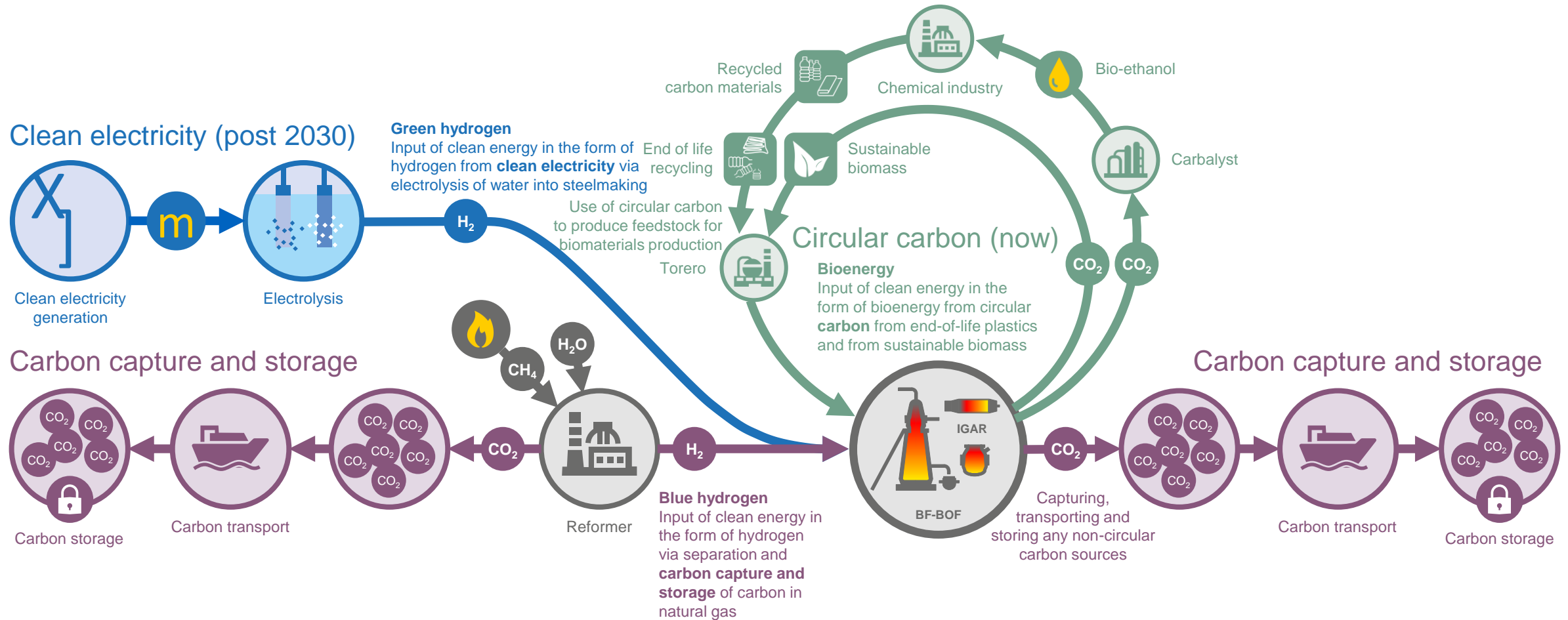
Key

- A. Steelmaking transformation (footprint change, energy efficiency, pellets)
- B. Energy transformation (CCUS, hydrogen, bioenergy)
- C. Increased scrap use
- D. Sourcing clean electricity
- E. Offsetting residual emissions

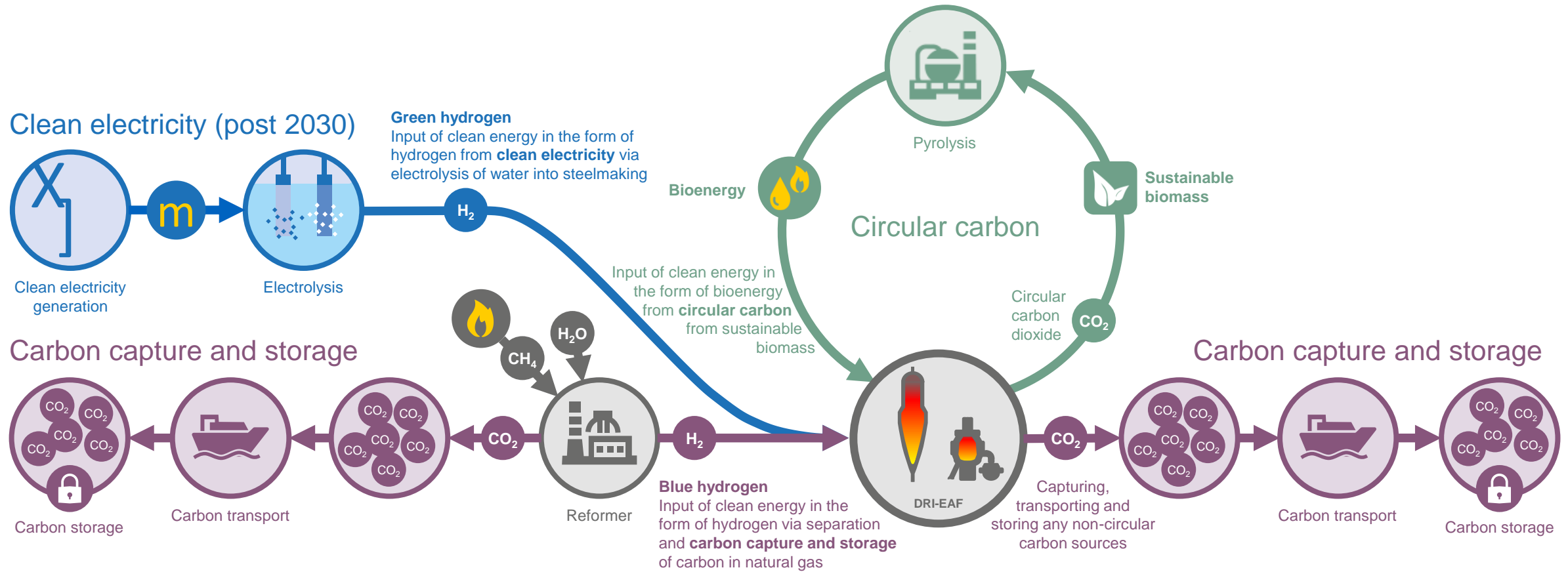
The background of the slide is a blurred photograph of a modern office interior. Several people are visible, standing and talking, their figures out of focus. The lighting is soft, and the overall color palette is muted, with a dark teal overlay. The text is centered in a clean, white, sans-serif font.

The 3 steelmaking routes toward decarbonisation

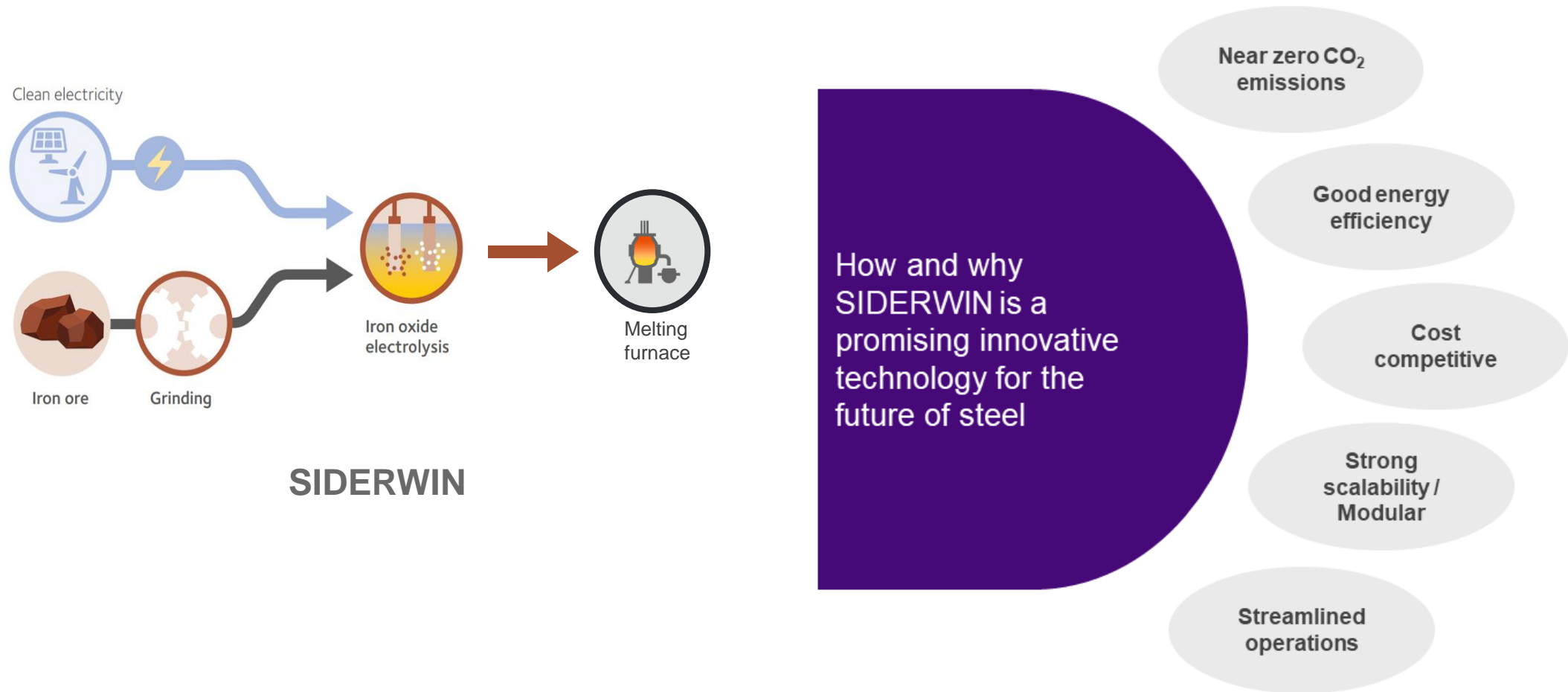
Making carbon-neutral steel: the **Smart Carbon route**




Making carbon-neutral steel: the DRI-based route



Making carbon-neutral steel: the **Direct electrolysis route**



The background is a dark, artistic composition of technical drawings and mechanical parts. It includes various engineering sketches, cross-sections, and detailed views of components like a bearing, a lens, and a small metal bracket. The drawings are overlaid on a dark, textured surface, possibly wood or a dark cloth, creating a professional and technical atmosphere.

Thank you
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Questions?



Development of new methodologies **S** for In**D**ustrial
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Iron Electrowining – Lessons learned

Daniela Lopes, Aleksey Lisenkov, Andrei Kavaleuski (Kovalevsky)

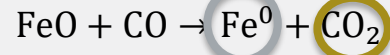
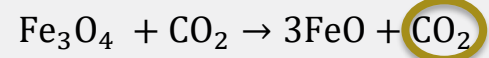
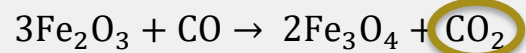
University of Aveiro

Webinar March 23rd 2023

Traditional ironmaking route vs ironmaking by electrolysis

Traditional route

BLAST FURNACE (~2000 °C)



Purification and iron melting for steel production

71% of iron production worldwide

19-15 GJ/ton Fe produced^{1,2}

Electrochemical-based route

- acidic/alkaline conditions;
- low temperature;
- H₂ and O₂ production as by-products due to water splitting.

CO₂ free technology



13 GJ/ton Fe produced^{1,3}

¹DOI: 10.1007/978-94-017-2728-0

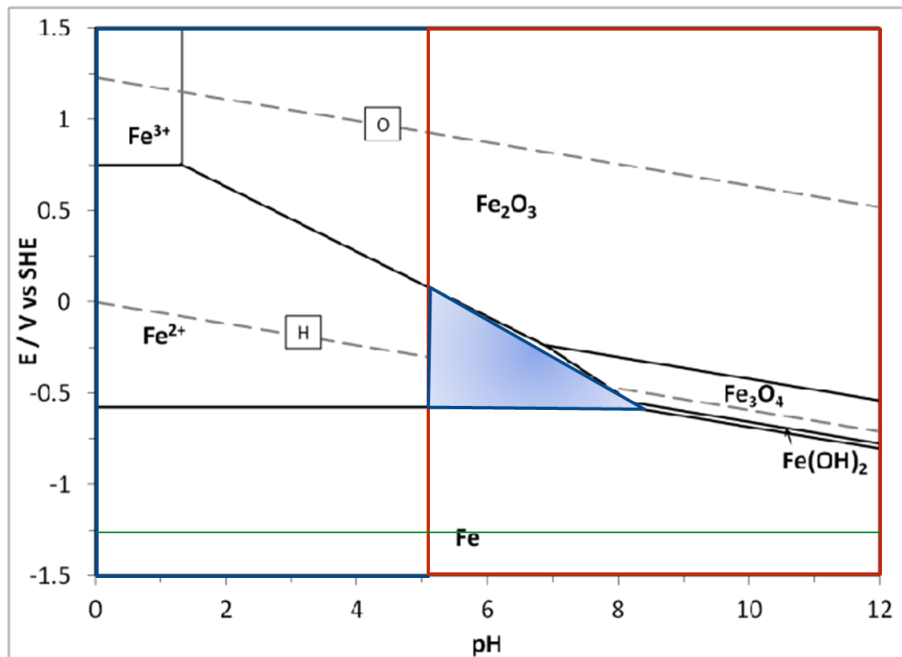
²DOI: 10.1016/B978-0-08-096988-6.00001-8

³DOI: 10.1007/s10800-010-0172-0

Electrowinning of iron – alkaline or acidic medium?

Iron oxide reduction is feasible under both acid and alkaline conditions

Pourbaix diagram of iron species (25 °C)



Tanaporn Tanupabrunsun, 2012

Previous lesson learned:

Acidic conditions:

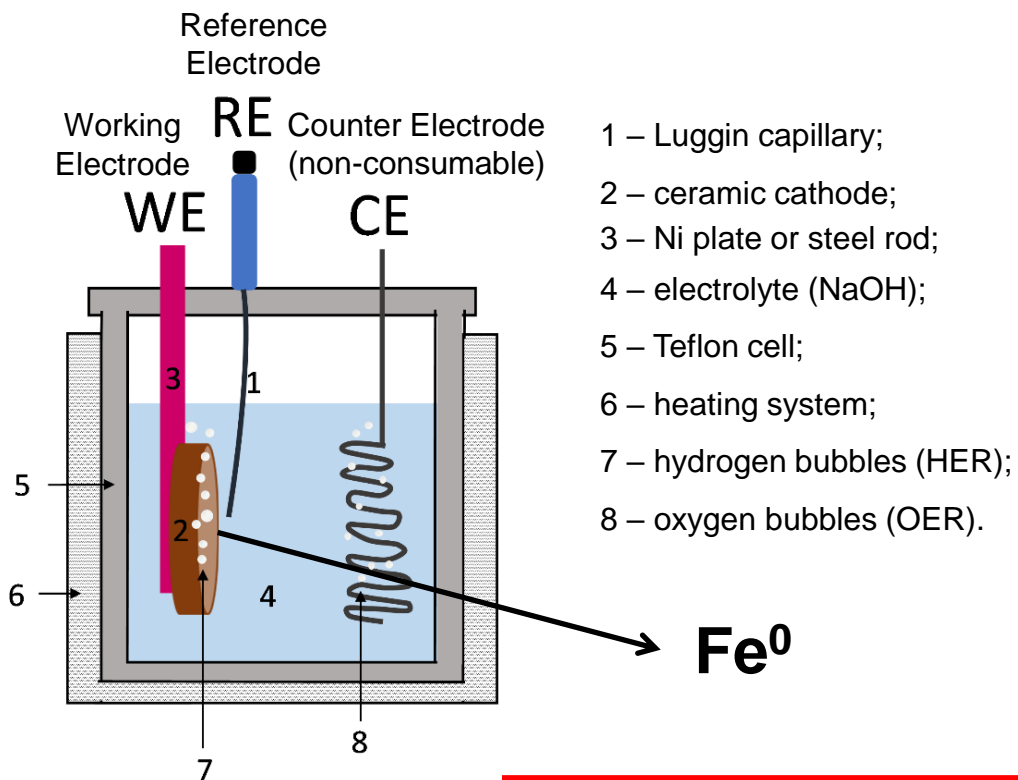
- Fe²⁺ and Fe³⁺ co-exist in the acidic electrolytic bath, forming a redox cycle loop between the iron species, lowering the overall Faradaic efficiency.
- Brittle iron deposits are often obtained in acidic baths.
- Concurrent hydrogen evolution.

The use of alkaline conditions prevents/mitigates these effects and leads to higher current efficiencies.

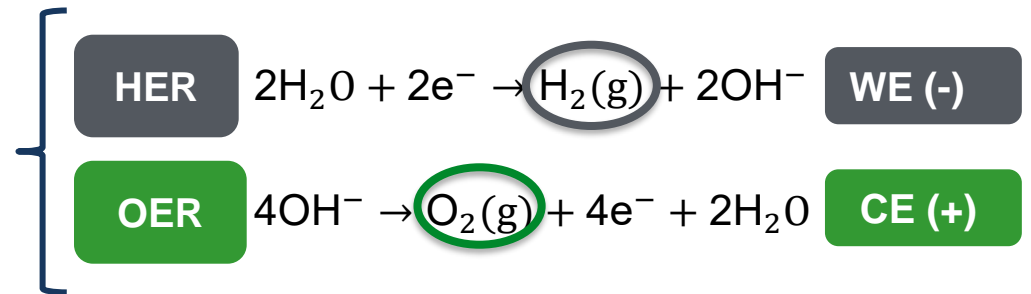
Electrowinning in alkaline media – general concepts

Experimental conditions:

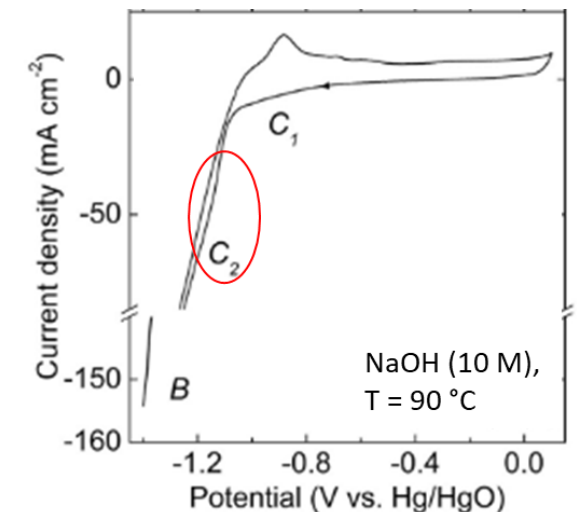
- strong alkaline conditions (electrolyte: NaOH, from 5 up to 18 M);
- low temperatures: from room temperature up to 110 °C.



Water splitting in alkaline medium....



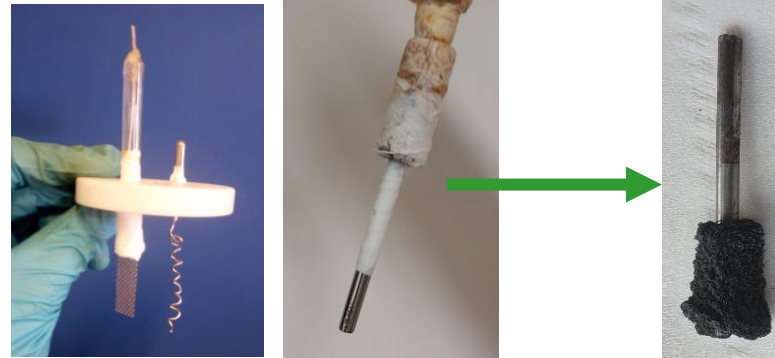
Lesson learned:
H₂ competes with Fe for the cathodic current, decreasing the efficiency of the reduction



Electrochemical reduction: bulk vs suspensions modes

Two approaches for electroreduction:

I) Powder Suspensions



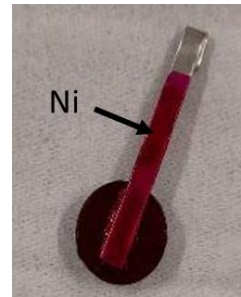
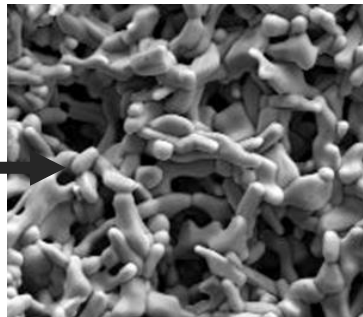
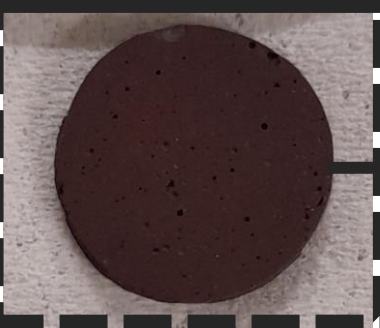
Cathode

Iron electrowinning cell (solid phase or suspension)



Electrochemical cell from NTUA

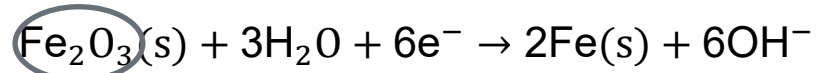
II) Bulk



Cathode

**Strong alkaline conditions
(NaOH, 5 to 18 M), $T \sim 100\text{ }^{\circ}\text{C}$**

Electrochemical reduction: bulk vs suspensions modes

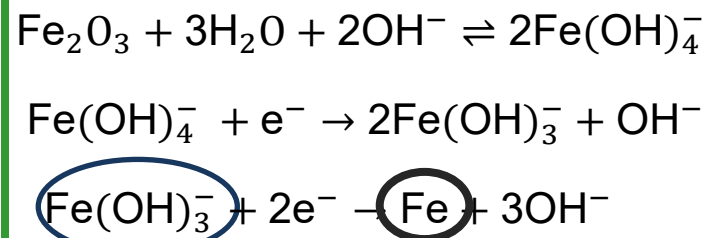
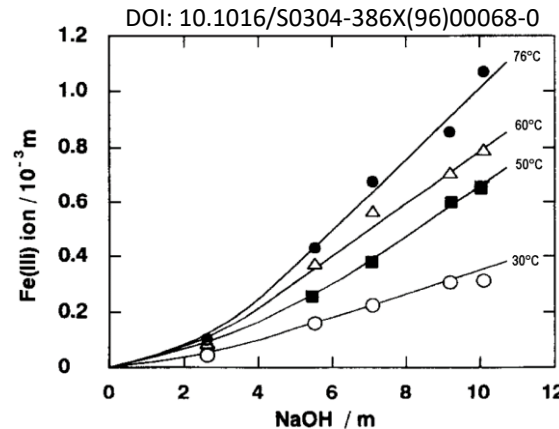
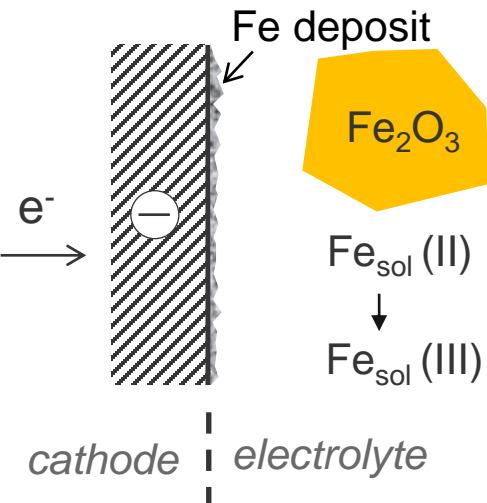


Electrical insulator (10^{-14} S/cm)

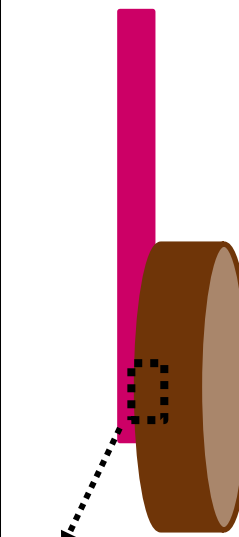
Which are the mechanisms of reduction of Fe(III) to Fe⁰?

Mechanism of reduction in suspension mode:

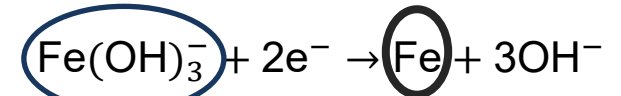
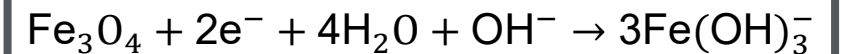
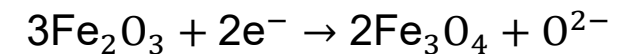
Alkaline conditions facilitate the reductive dissolution of Fe₂O₃



Mechanism of reduction in bulk cathode mode:



CC: current-collector



Iron electrowinning: lessons learned through case studies

Hematite suspensions

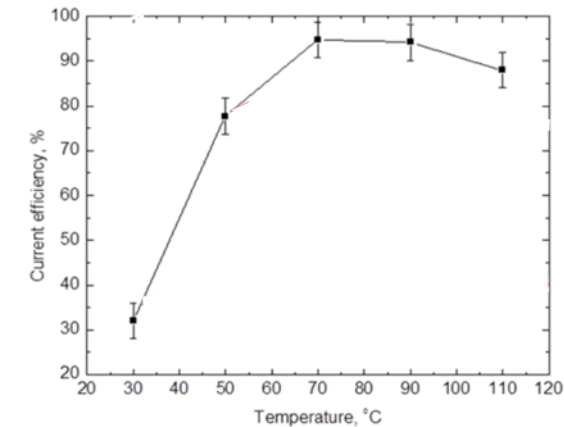
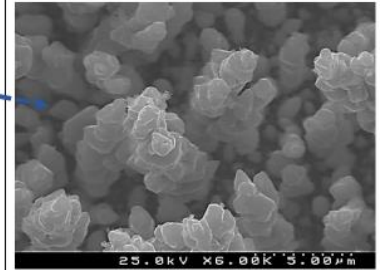
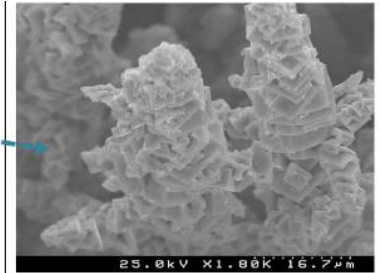
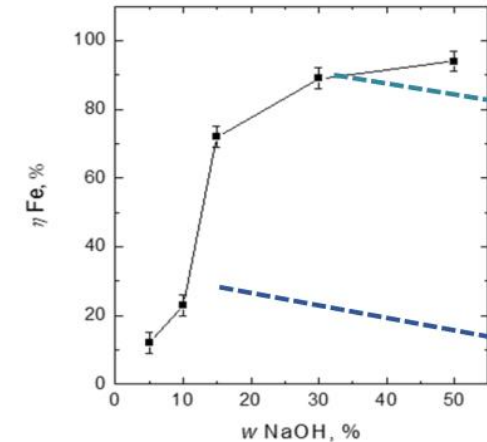
Lessons learned:

- Iron electrowinning from Fe_2O_3 suspensions is feasible and current efficiencies of >90% can be attained depending on the experimental conditions used;
- Higher concentrated electrolytes (30 to 50 wt% - ~10 to ~18 M NaOH) and temperatures between 70 to 80 ° C play an important role for obtaining higher current efficiencies.



These experimental conditions facilitate the reductive dissolution of the iron oxides into aqueous iron(III) and (II) species.

90 °C, 100 g/L Fe_2O_3 , 0.033 A/cm² and 100 rpm

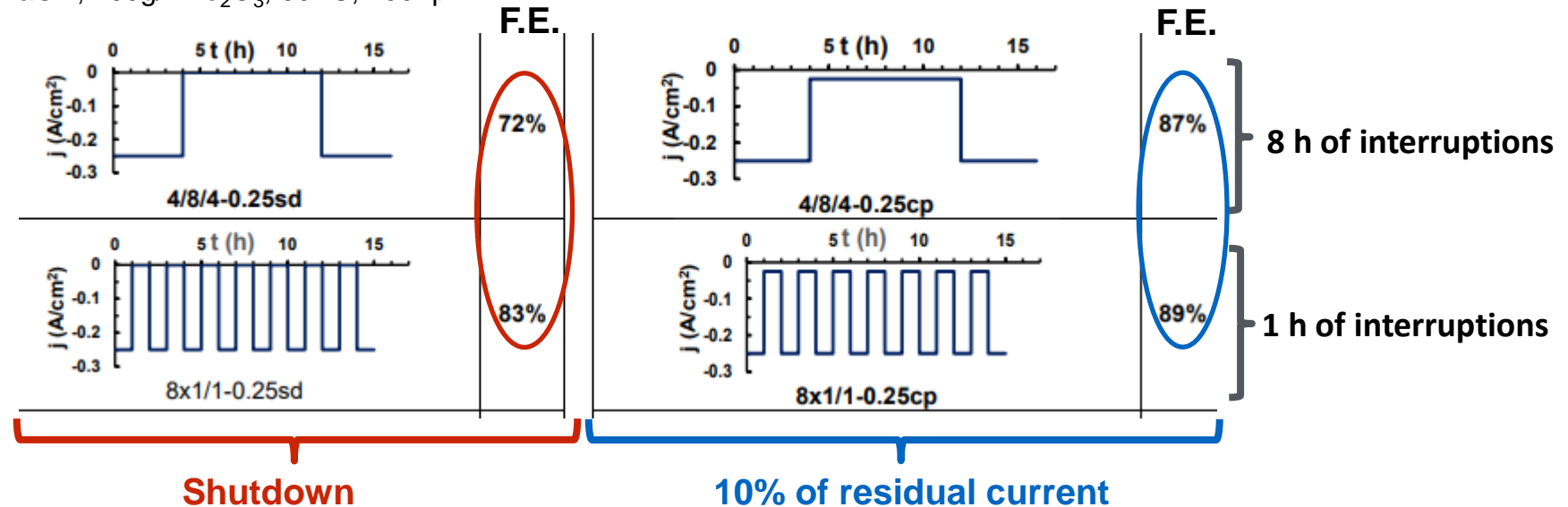


100 g/L Fe_2O_3 , 0.033 A/cm² and 100 rpm

Iron electrowinning: lessons learned through case studies

Cycles with shutdown interruptions or cathodic protection (10% of residual current) for Fe electrowinning from Fe_2O_3 suspensions

18 M NaOH, 200g/L Fe_2O_3 , 90 °C, 100 rpm

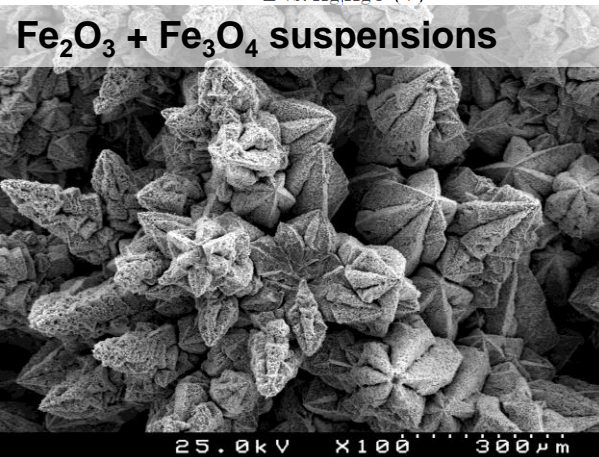
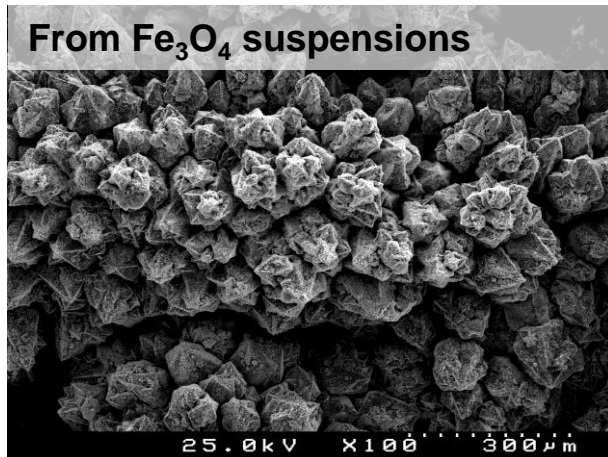
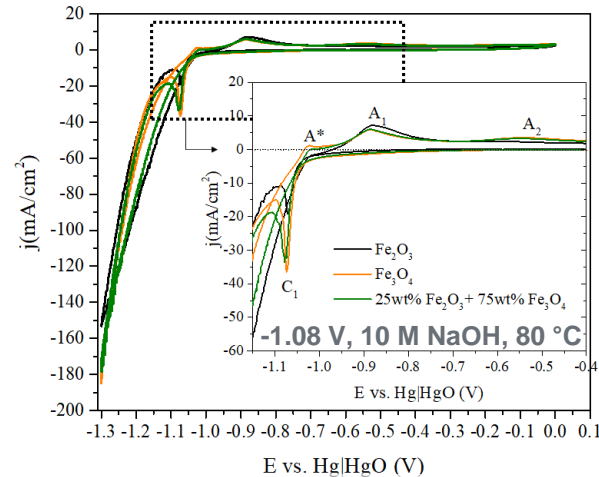
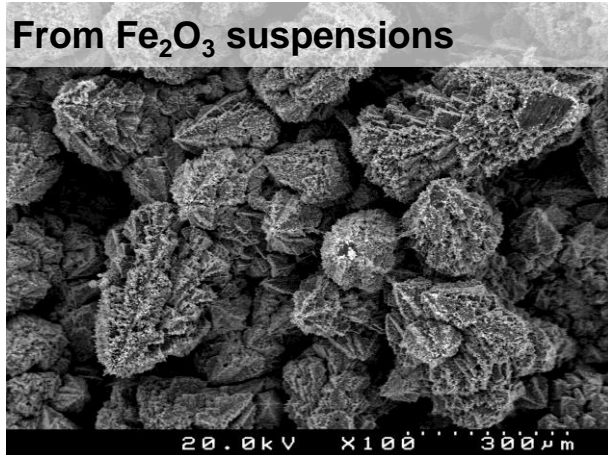


Lessons learned:

- shutdowns cause a more accentuated cathodic oxidation and higher potentials (~ -1.18 V) when longer interruptions are applied (8 h) \rightarrow lower current efficiencies;
- shorter and frequent interruptions (1h) keep the potential slightly above -1.0 V and minimize risks of iron oxidation (shutdown case).

Iron electrowinning: lessons learned through case studies

Hematite and magnetite: suspensions

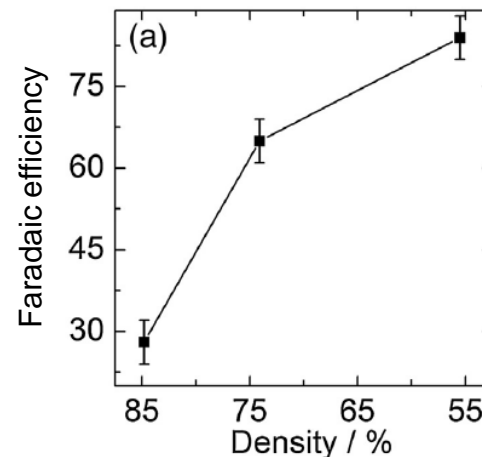
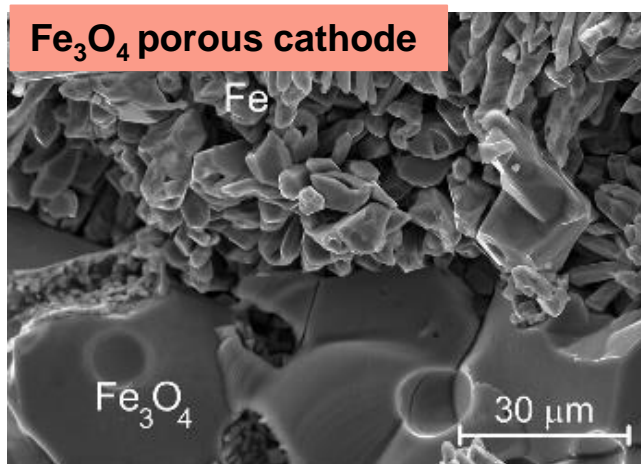
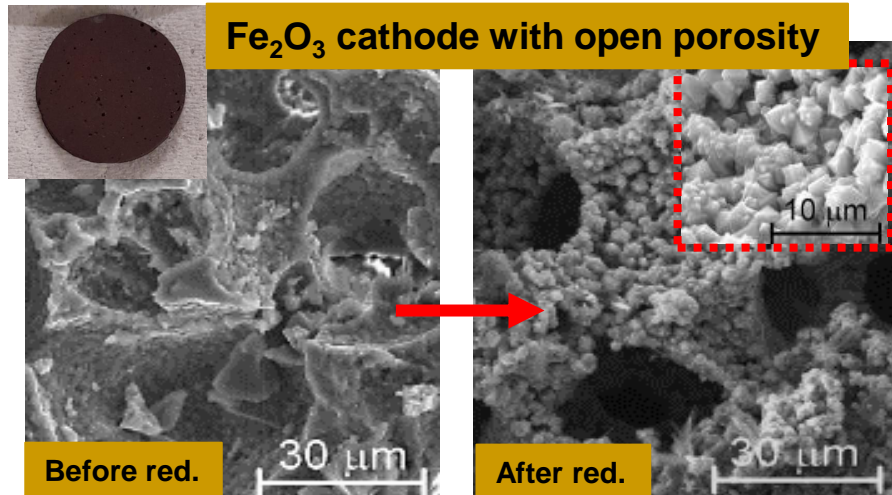


Lessons learned:

- It is feasible to use Fe_3O_4 as an iron oxide feedstock for the iron electrowinning → previous studies suggested 5% of faradaic efficiencies, but 69% can be attained when using mechanical stirring instead of magnetic;
- Mixtures containing Fe_2O_3 - Fe_3O_4 (25 wt% vs 75 wt%) showed efficiencies higher than 65% in all cases tested;
- Iron ores with high content of magnetite can be used as a feedstock;
- Perspective for using metallurgical residues rich in magnetite.

Iron electrowinning: lessons learned through case studies

Hematite and magnetite: bulk cathodes



Lessons learned:

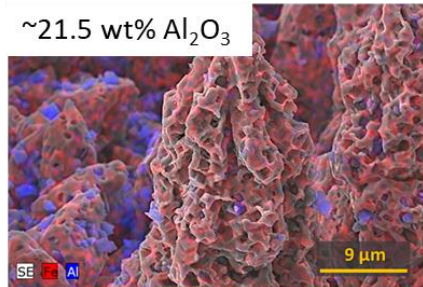
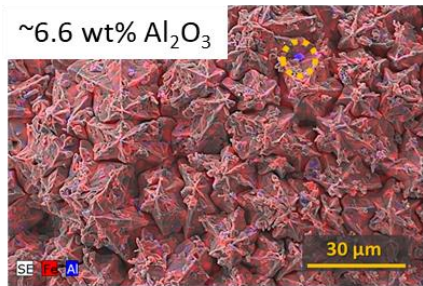
- The reduction of dense pellets is restricted to the area near the current collector → lower faradaic efficiencies;
- Open porosity of bulk cathode allows the percolation of the electrolyte and further reduction to Fe₃O₄ (intermediate step for the reduction to Fe) → higher efficiencies (above 80%);
- Iron ores pieces can be used for this purpose → low efficiencies without porosity (< 30%).

Bulk cathode concept is interesting for studying the iron oxides reduction mechanisms and effects of various potential impurities (e.g., Al, Ti,...), but have limited prospects for industrial process.

Iron electrowinning: lessons learned through case studies

Al

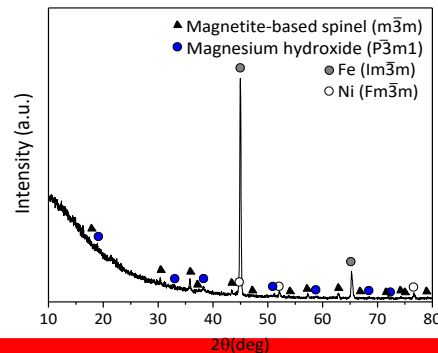
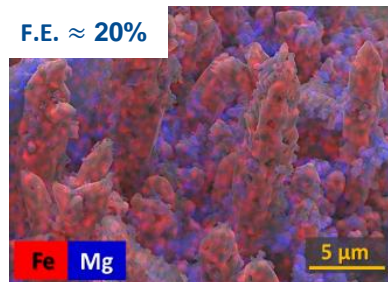
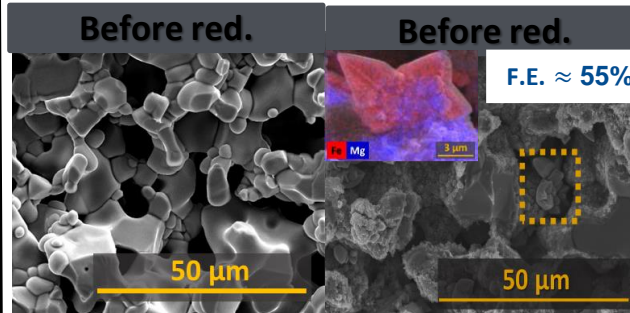
-1.08 V, 6h, 10 M NaOH, 90 °C



When increasing Al content, the efficiency of electrochemical reduction of Fe(III) to Fe⁰ decreases from 70% to 32%

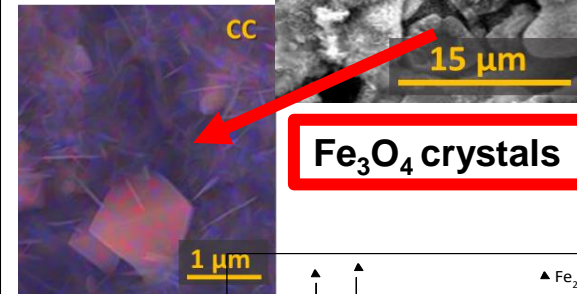
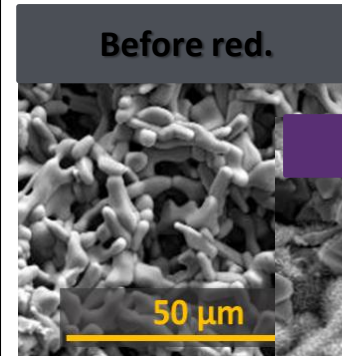
Mg

-1.14V, 6h, 10 M NaOH, 90 °C

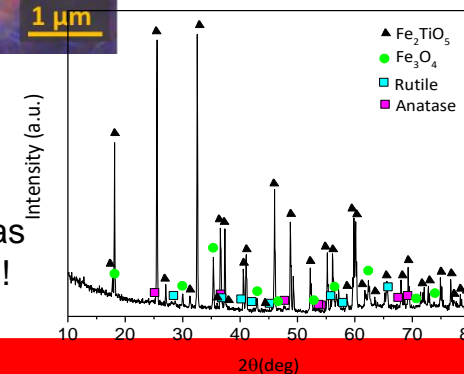


Ti

-1.15 to -1.30 V, 7h, 10 M NaOH, 90 °C



No Fe was obtained!!




→ non-conductive phases

Lessons learned:

- The presence of non-conductive phases (bulk or suspensions) leads to the partial blocking of the electrochemically active surface of the cathodes;
- Corresponding kinetic limitations result in consequent decrease of the faradaic efficiency.

Summary

- Iron electrowinning from pure Fe_2O_3 suspensions is feasible with high faradaic efficiencies (90 %).
- Iron electrowinning can be made feasible even under intermittent conditions provided by renewable sources, particularly if cathodic protection can be implemented.
- Iron electroreduction can be achieved using either bulk cathode or from an oxide suspension, with the latter being more suitable for industrial processes.
- Iron electrowinning from Fe_3O_4 suspensions is also feasible.
- The presence of non-conductive impurities (e.g., Al, Mg, Ti..) results in partial blocking of the electrochemically active surface of the cathodes, leading to slower kinetics and lower faradaic efficiencies.

The background is a dark, artistic composition of technical drawings and mechanical parts. It includes various engineering sketches, cross-sections, and detailed views of components like a bearing, a lens, and a small metal bracket. The drawings are overlaid on a dark, textured surface, possibly wood or a dark cloth, creating a professional and technical atmosphere.

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Questions?



Development of new methodologies for Industrial
CO₂-free steel production by electro-winning

Alternative feeding materials.
Current status and future perspectives.

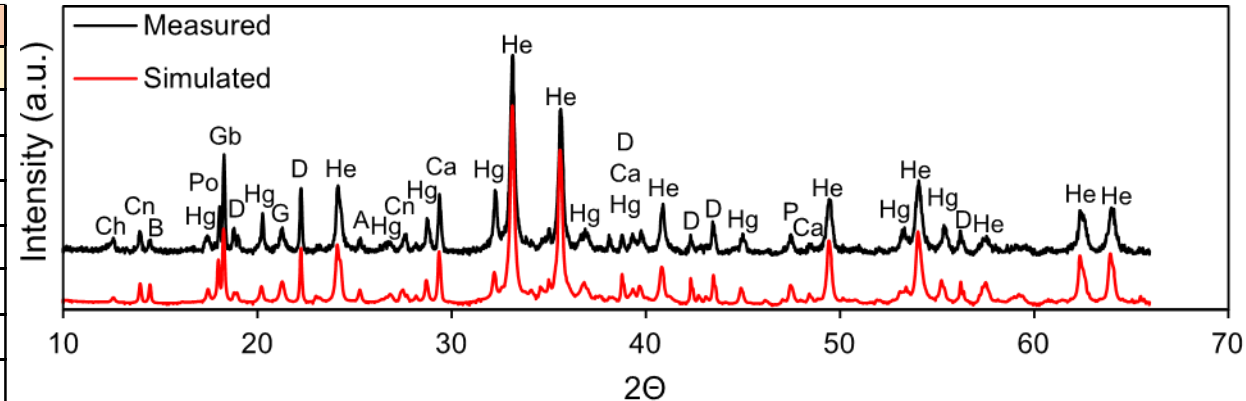
Prof. Dimitrios Panias – NTUA
Webinar March 23rd 2023

The case of Bauxite Residue

- ❑ Bauxite Residue (BR) is a by-product of Alumina Refining with the Bayer Process.
- ❑ It is mainly the residue of the bauxite digestion with caustic soda.
- ❑ It is actually the filter cake of Red Mud filtration in filter presses.
- ❑ 170 million tons are produced annually worldwide and 6.8 million tons are produced in Europe.

Bauxite Residue Sample from the Mytilineos Greek Plant

% w/w Chemical Analysis	
Species	BR
Fe ₂ O ₃	44.77
Al ₂ O ₃	18.75
SiO ₂	6.69
CaO	9.77
Na ₂ O	2.93
TiO ₂	6.65
LOI	9.17



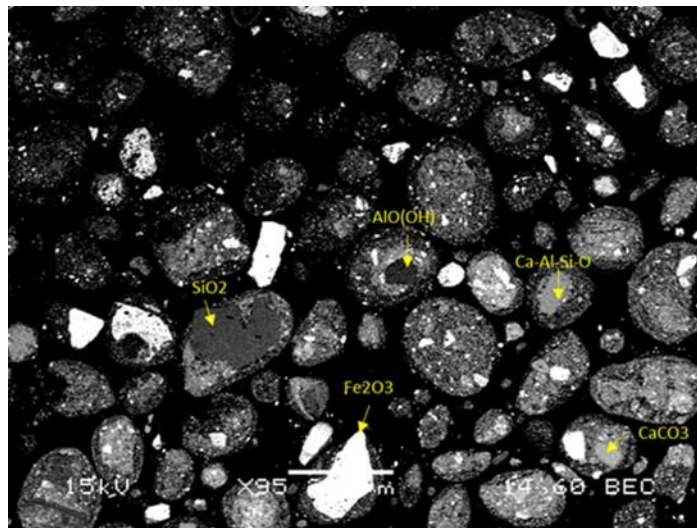
He	Hematite
Hg	Hydrogarnet
D	Diaspore
Cn	Cancrinite
G	Goethite
Ca	Calcite
P	Perovskite
Ch	Chamosite
Gb	Gibbsite
B	Boehmite
Po	Portlandite
R	Rutile
A	Anatase

Quantification of Mineralogical phases

	Hematite	Hydrogarnet	Diaspore	Cancrinite	Goethite	Calcite	Perovskite	Chamosite	Gibbsite	Boehmite	Portlandite	Rutile	Anatase	Quartz	Total
	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%
Bauxite residue	31	14.5	13	11	7.5	5	4	3.7	2.5	2	0.8	0.7	0.6	0.3	96.6

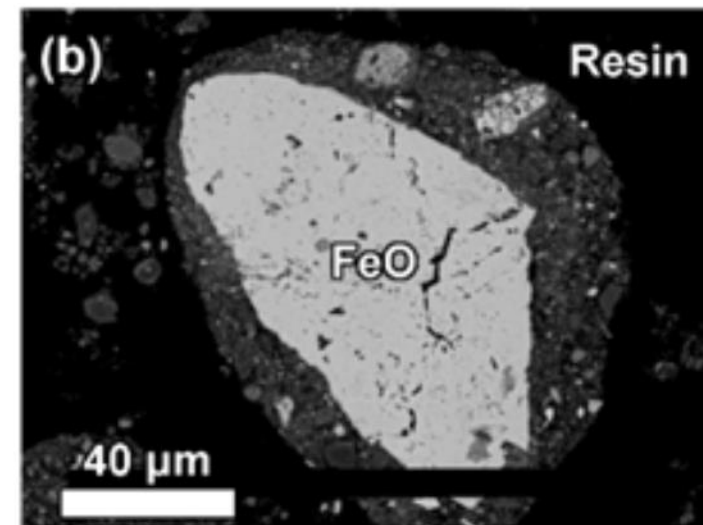
The case of Bauxite Residue

BR has complex mineralogy and is strongly agglomerated with the iron-bearing phases to be entrapped in the BR matrix.



typical bauxite residue
macrostructure

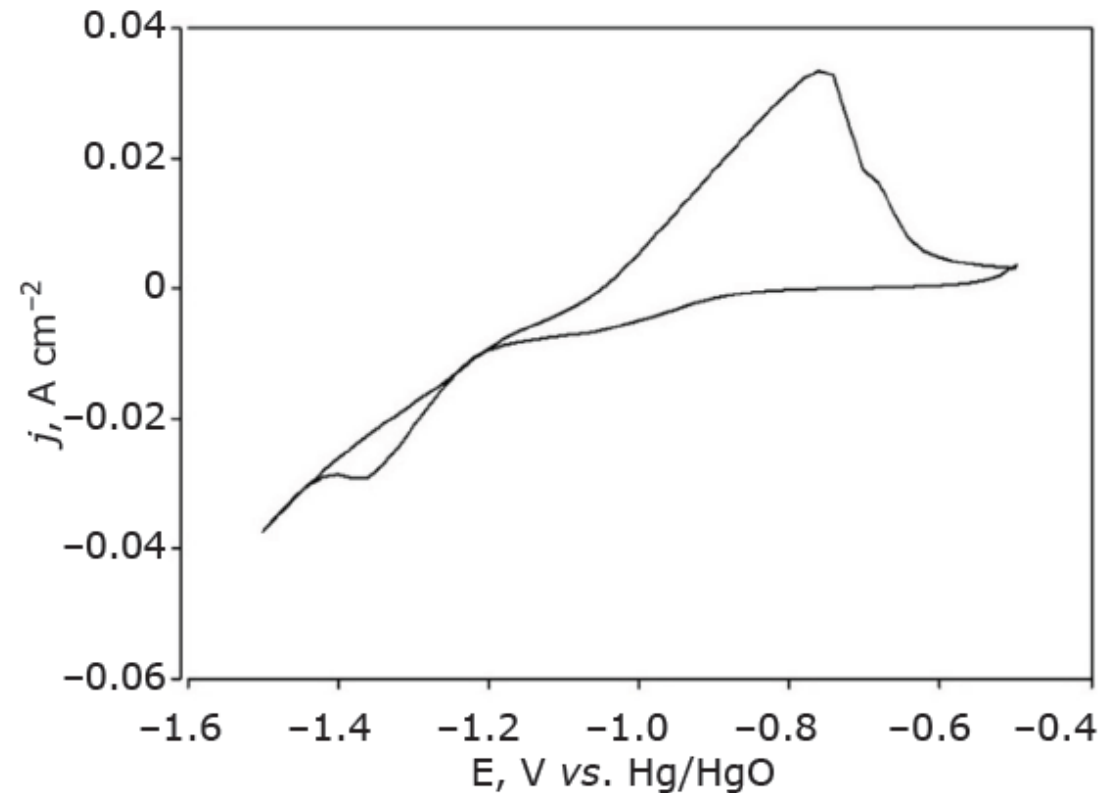
strong agglomeration



typical bauxite residue's Fe oxide
particle (denoted as FeO)
entrapped Iron Oxide particle in the
BR matrix

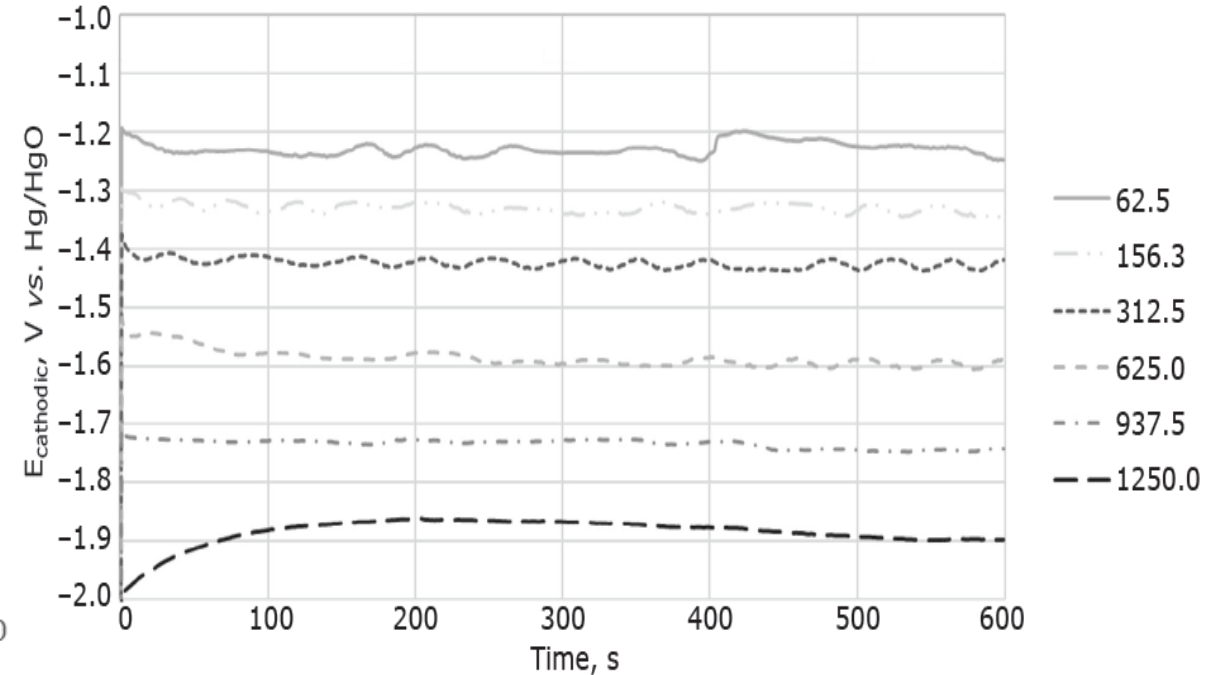
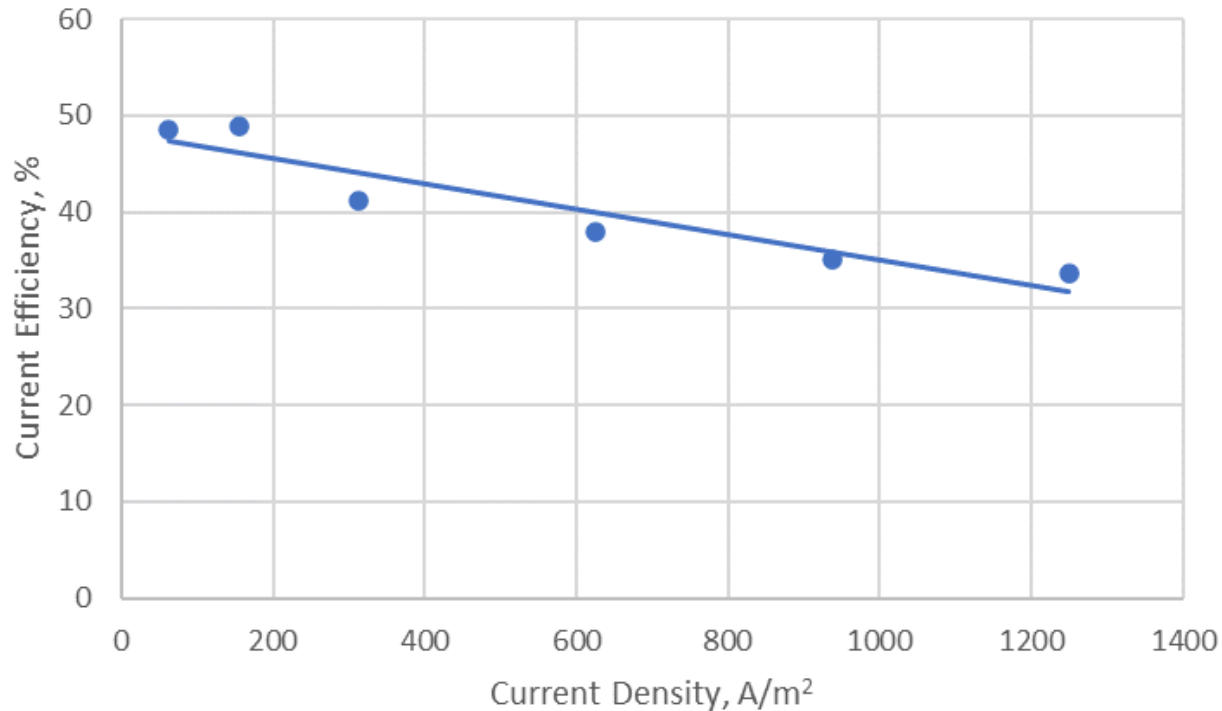
Alkaline BR Electrolysis

- Iron deposition is taking place in the cathodic potentials region -1.4 V to -1.2 V vs Hg/HgO.
- Hydrogen evolution is taking place at cathodic potentials lower than -1.4 V vs Hg/HgO.
- The plateau at cathodic potentials -1.2 V to -0.9 V vs Hg/HgO is attributed to the reduction of hematite to magnetite.



Cyclic Voltammogram of 10 %wt BR pulps in 50 %wt NaOH solution at 110 °C and a scanning rate of 100 mV.s^{-1} .

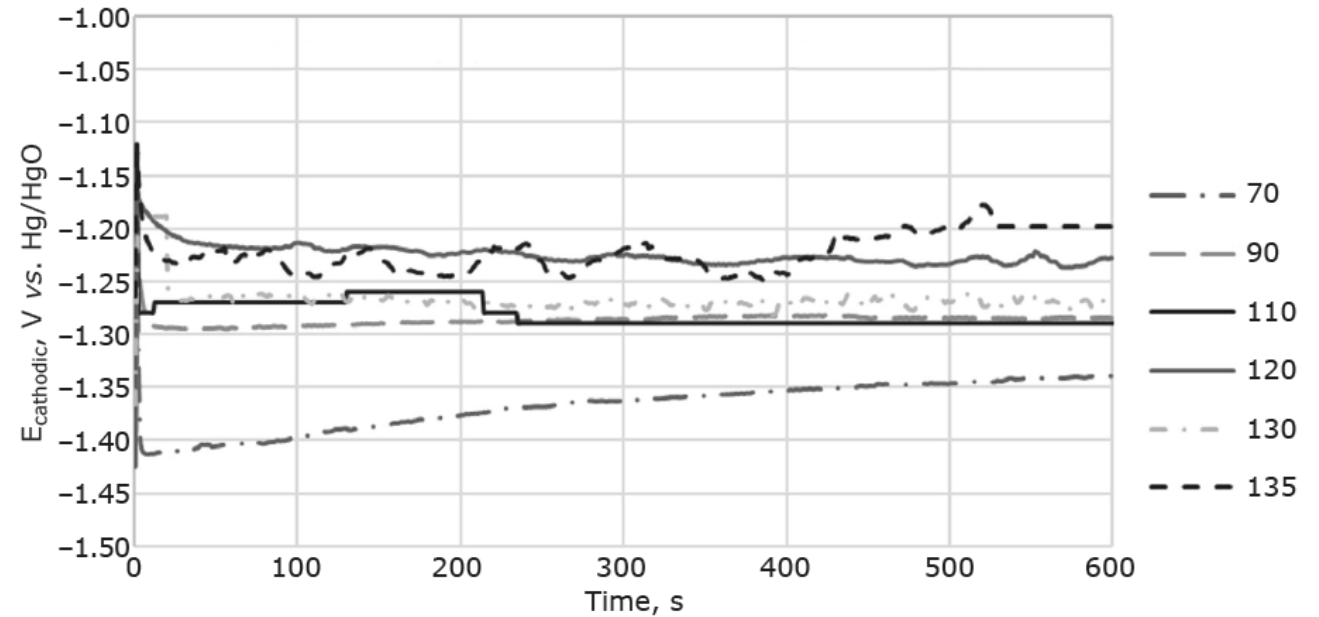
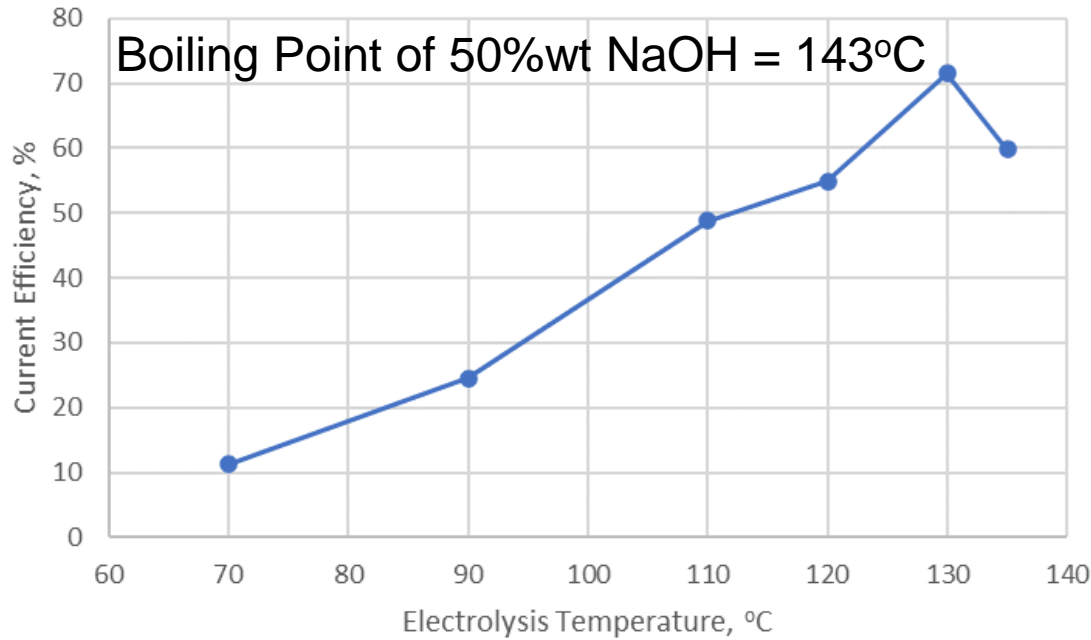
Effect of current density on Current Efficiency



10 %wt BR Pulp density in 50 %wt NaOH solution at 110 °C and a stirring rate of 500 rpm in a cylindrical cell with 2 Ni plates as anodes and 1 Stainless Steel plate as cathode. Hg/HgO/NaOH (1M) was used as Reference electrode. Duration 2h.

- ❑ The current efficiency is, in general, low. Lower than 50%, a value substantially lower the one of hematite electrolysis (85 – 95%).
- ❑ The lower the current density, the higher the current efficiency is.
- ❑ Current densities higher than 312.5 A/m² polarize the cathodic potential to the region of hydrogen evolution.

Effect of Temperature on Current Efficiency



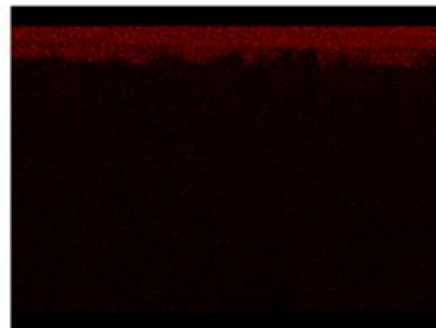
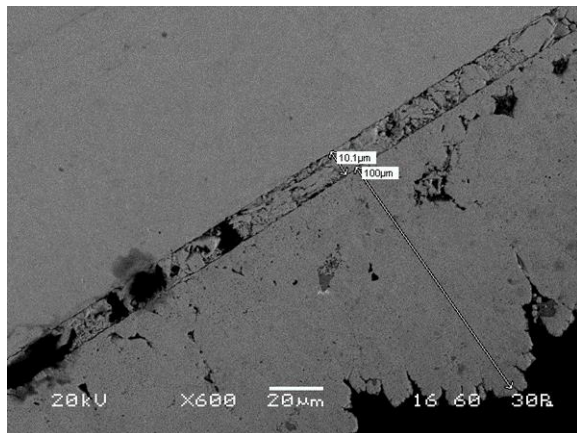
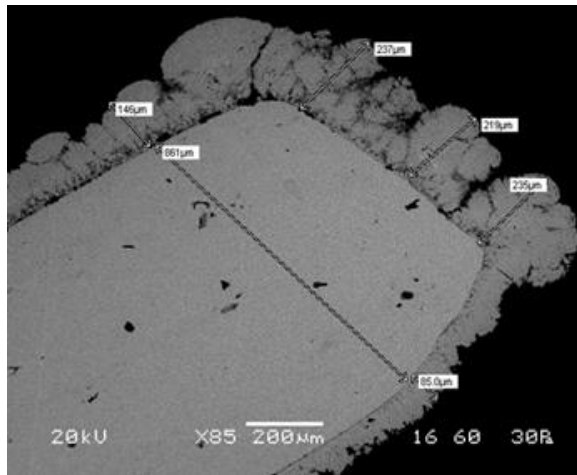
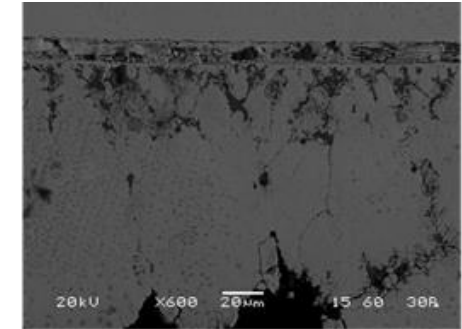
10 %wt BR Pulp density in 50 %wt NaOH solution at 156.3 A/m^2 and a stirring rate of 500 rpm in a cylindrical cell with 2 Ni plates as anodes and 1 Stainless Steel plate as cathode. Hg/HgO/NaOH (1M) was used as Reference electrode. Duration 2h.

- ❑ The current efficiency increases, almost linearly, from 70 to 130 °C and then starts decreasing.
- ❑ There is a tendency towards lower cathodic potentials as the electrolysis temperature decreases which coincides with the lower current efficiencies due to the hydrogen evolution.

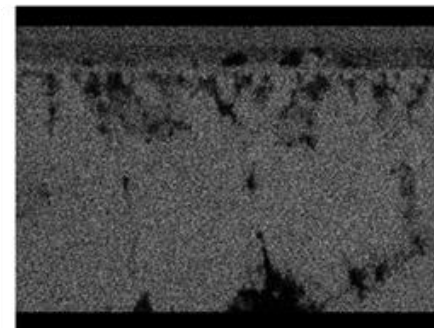
Long term electrochemical behaviour of BR suspensions

- ❑ The Current efficiency decreases with the time.

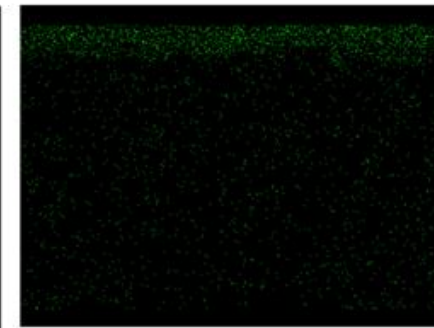
Calcium Titanates have accumulated inside the massive 2nd Iron deposition layer and possibly passivate and polarize the cathode to potentials favoring the hydrogen evolution.



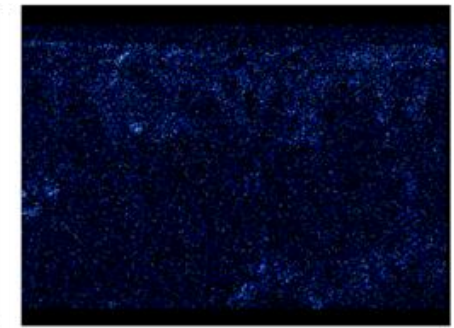
Cr Ka1



Fe Ka1



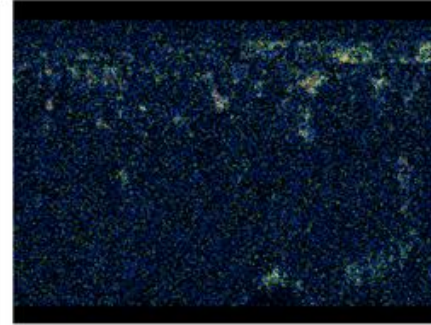
Ni Ka1



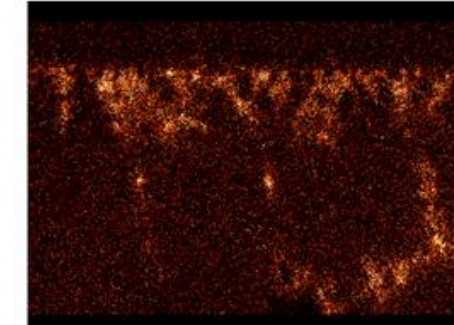
O Ka1



Si Ka1



Ca Ka1

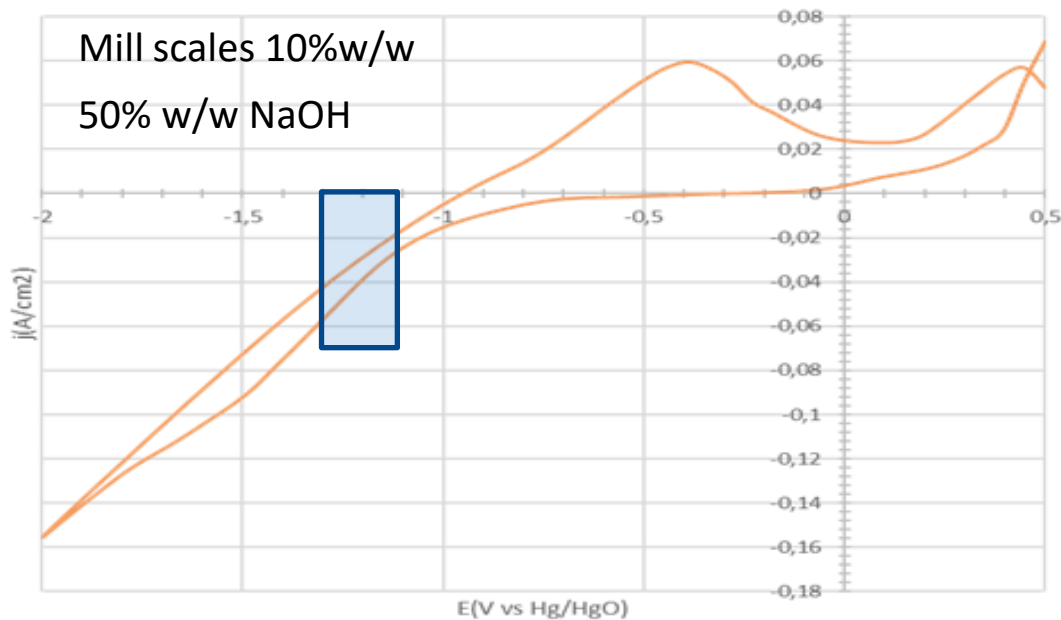


Ti Ka1

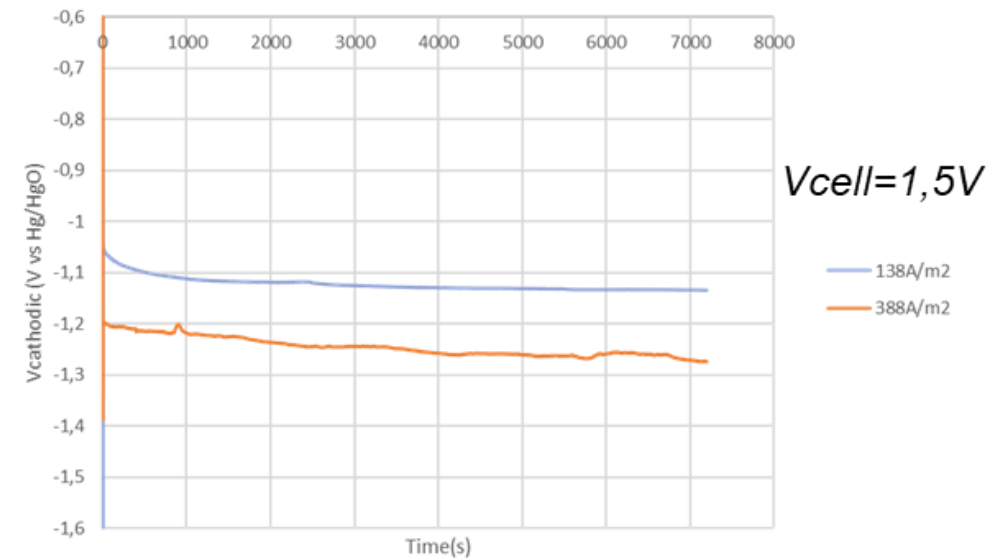
OTHER ALTERNATIVE RAW MATERIALS

- ❑ **Mill Scales** are formed on the outer surfaces of plates, sheets or profiles when they are being produced by rolling red hot iron or steel billets in rolling mills.

Cyclic Voltammetry(100mV/s -95°C)



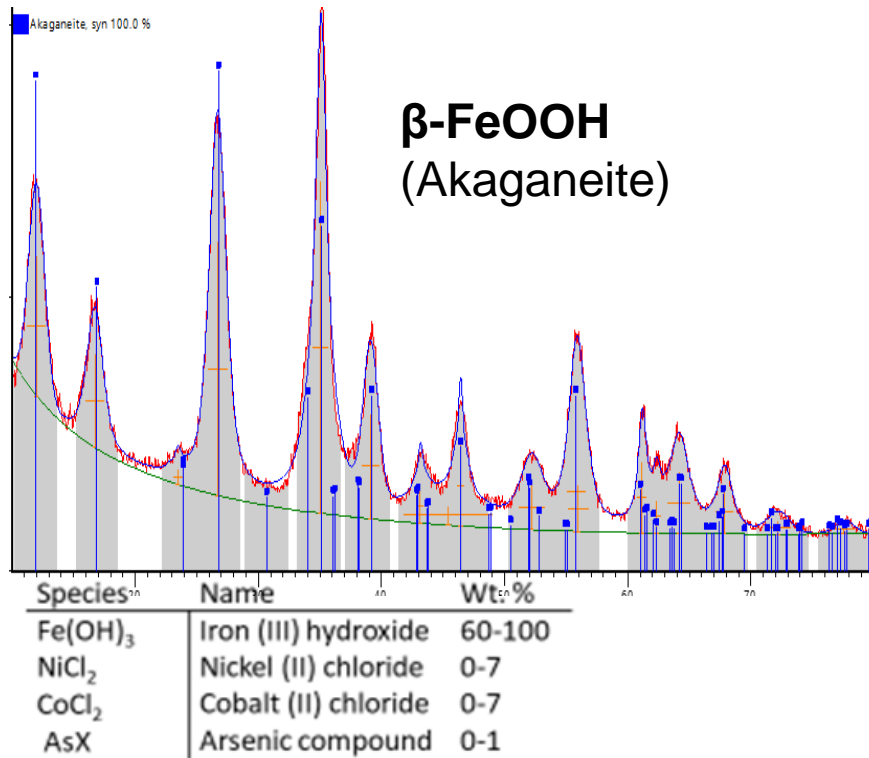
Mills scale galvanostatic experiments with different current density



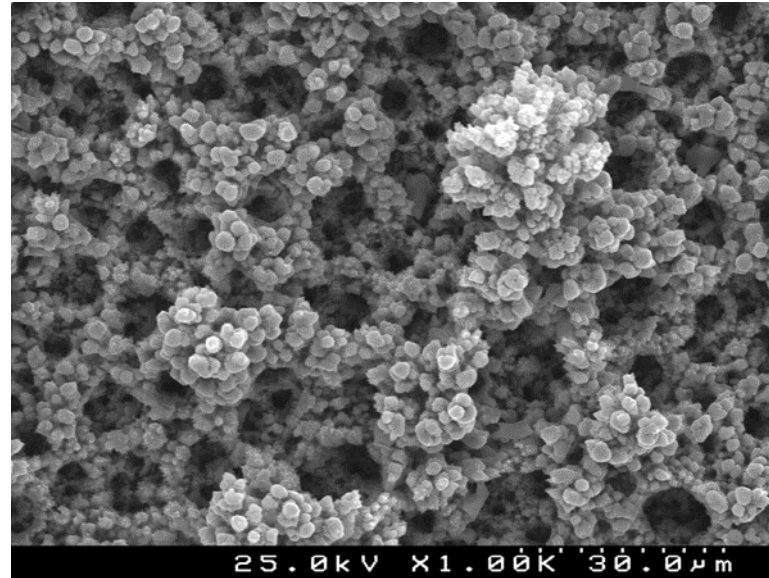
Current density(A/m²)	Efficiency(%)
138	91,88
388	97,13

OTHER ALTERNATIVE RAW MATERIALS

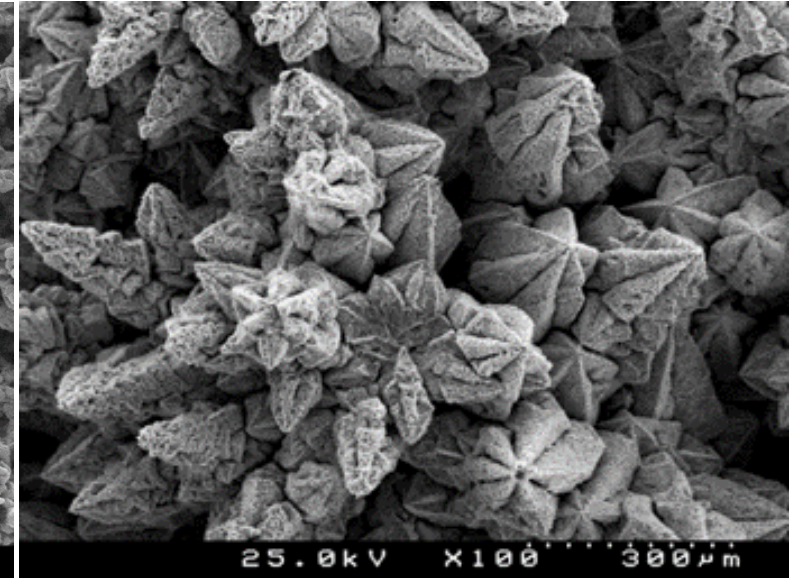
- ❑ **Iron Sludges** coming from the separation of iron from NiCl_2 solution by $\text{Cl}_2(\text{g})$ and NiCO_3



The material is fine with $\text{D}_{50} < 10 \mu\text{m}$ [Nikkelverk]



- Fe deposits from the Nikkelverk sludge suspension have porous structures and consist in small spherical crystals.



- Fe deposits from the Hematite suspension have a non-porous microstructure with well-defined dendritic crystals.

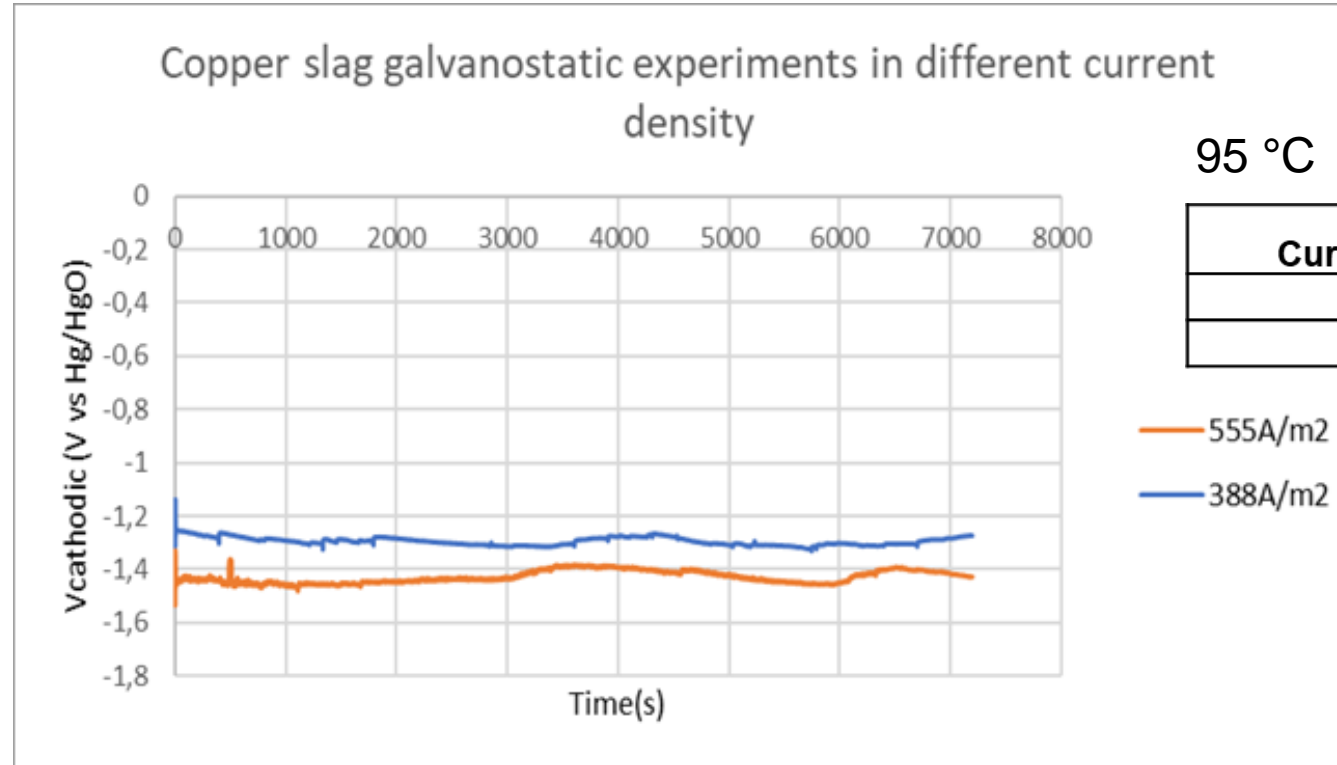
The current efficiencies achieved are in-between 10 – 40%

OTHER ALTERNATIVE RAW MATERIALS

- ❑ **Ferritic Slags** coming from the Copper or Ferronickel Pyrometallurgical processing

Slag from Copper Industry

Chemical Analysis	
oxide	% w/w
FeO	44,41
Al ₂ O ₃	3,30
SiO ₂	39,95
TiO ₂	0,22
Na ₂ O	1,05
CaO	4,08
Cr ₂ O ₃	0,25
ZnO	2,14
MgO	1,77
MnO	0,52
MoO	0,21
CuO	0,85
K ₂ O	0,38
BaO	0,21
CoO	0,10
SnO ₂	0,17
TOTAL	99,61




Current density(A/m2)	Efficiency(%)
388	20,172
555	30,967

- Iron deposition is taking place in the cathodic potentials region -1.5 V to -1.1 V vs Hg/HgO.
- Currents are almost double the ones observed in BR CV under the same conditions.

The main problem was the dissolution of SiO₂ in the electrolyte and its polymerization that increase the viscosity and thus hinders the iron deposition.

CONCLUSIONS

- ❑ A variety of several iron-containing raw materials was tested as alternatives to iron ore feeding materials in SIDERWIN Process. Bauxite Residue from alumina production was the one studied in more detail followed by Mill Scales from iron rolling mills, Iron sludges from Nickel hydrometallurgical purification, and ferritic slags from copper and ferronickel production.
- ❑ Cyclic voltammetric studies showed that all the alternative materials have the potential to be used for Iron Production with the Siderwin Process.
- ❑ However, the current efficiencies achieved were low and the main reason for this general observation was the impurities that exist in these secondary iron-containing resources. Titanium and Magnesium proved to impede iron deposition.
- ❑ In the case of slags, the dissolution of silica in a strongly alkaline environment (50%wt NaOH) and its polymerization impede iron dissolution.
- ❑ Mill Scales seem to be the most promising alternative material at this stage of technology development. Mill Scales that contain iron in the mineralogical forms of Magnetite and Hematite perform very well giving iron deposition with very high current efficiencies. Mill Scales having as the main mineralogical phase Wustite do not perform well and must be oxidized before used in Siderwin Technology. Also, organics (several oils), exist inside Mill Scales, creating an inhibition on iron deposition, and therefore, they must be removed properly,
- ❑ Although, all alternatives were promising more work must be done in all of them before feeding the Siderwin Cell with them.

The background is a dark, artistic composition of technical drawings and mechanical parts. It includes various engineering sketches, cross-sections, and detailed views of components like a bearing, a lens, and a small metal bracket. The drawings are overlaid on a dark, textured surface, possibly wood or a dark cloth, creating a professional and technical atmosphere.

Thank you
for your attention

Questions?



Development of new methodologies for Industrial
CO₂-free steel production by electrolysis

Iron production by electrolysis at pilot scale

Thierry Conte – CFD Numerics

Salah Touhami – ArcelorMittal

Webinar March 23rd 2023

Contents

- The process development and design of the Siderwin pilot.
- The key process parameters for an efficient electrolysis of iron oxides into metallic iron.
- The assessment of electrolysis cell energy consumption.

A blurred, low-angle shot of an office interior. In the center, three people are standing and talking, their forms silhouetted against a bright light source, likely a window. Other figures are visible in the background, also blurred, suggesting movement. The floor is highly reflective, mirroring the silhouettes. The overall color palette is dark with a teal/cyan tint, and the text is white.

The Siderwin pilot

How to define an optimal electrowinning cell?

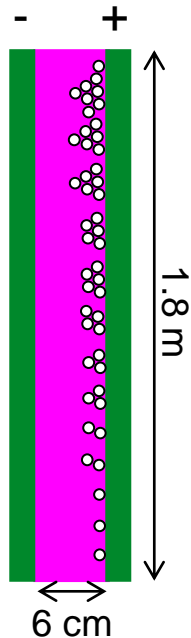
- **Main challenge:** find the right cell design to remove the large amount of oxygen bubbles generated by the electrolysis process.
 - Potential major issue: to get oxygen accumulation in the cell leading to a drastic loss of efficiency.
- Cell design: defined using CFD simulations.
 - **CFD for Computational Fluid Dynamics.**
 - Two-phase flows modelling in the cell to understand, analyse and optimize investigated designs.
- 1st step: the CFD model has been developed and validated.
 - Objective: to establish a **relevant methodology** to calculate **two-phase flows** (electrolyte and oxygen bubbles).
- 2nd step: CFD Models have been applied to design the cell and particularly define:
 - Cell angle to enhance the ability to drive bubbles out of the cell;
 - Anode design and implantation;
 - Degassing device to ensure a proper and smooth removal of generated oxygen bubbles;
 - Inlet distributor and outlet collector designs to reduce pressure drop and ensure a good flow uniformity;
 - Pump specification.

Oxygen bubbles management

Conventional electrowinning design is not applicable for Siderwin cell design.

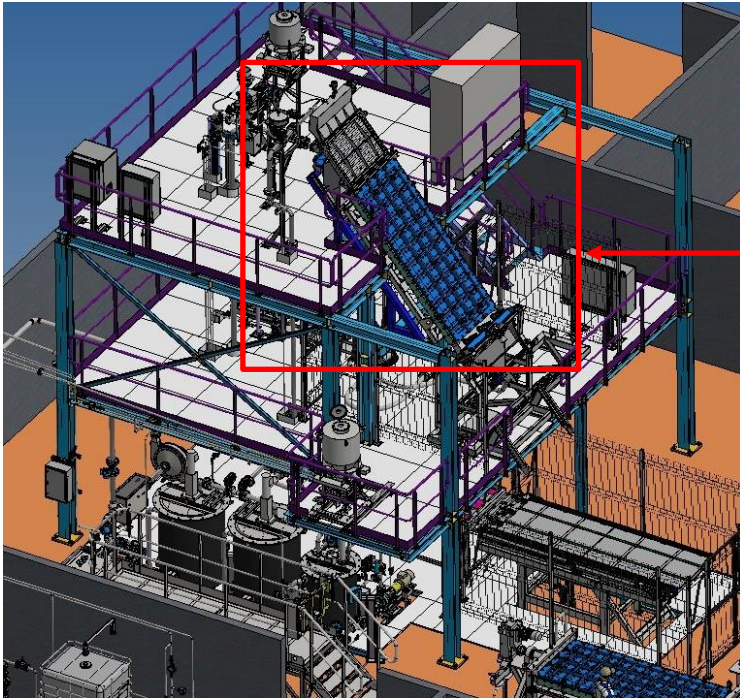
Large inter electrodes gap for bubbles and diaphragm.

Electrode extension limited by bubble screening.

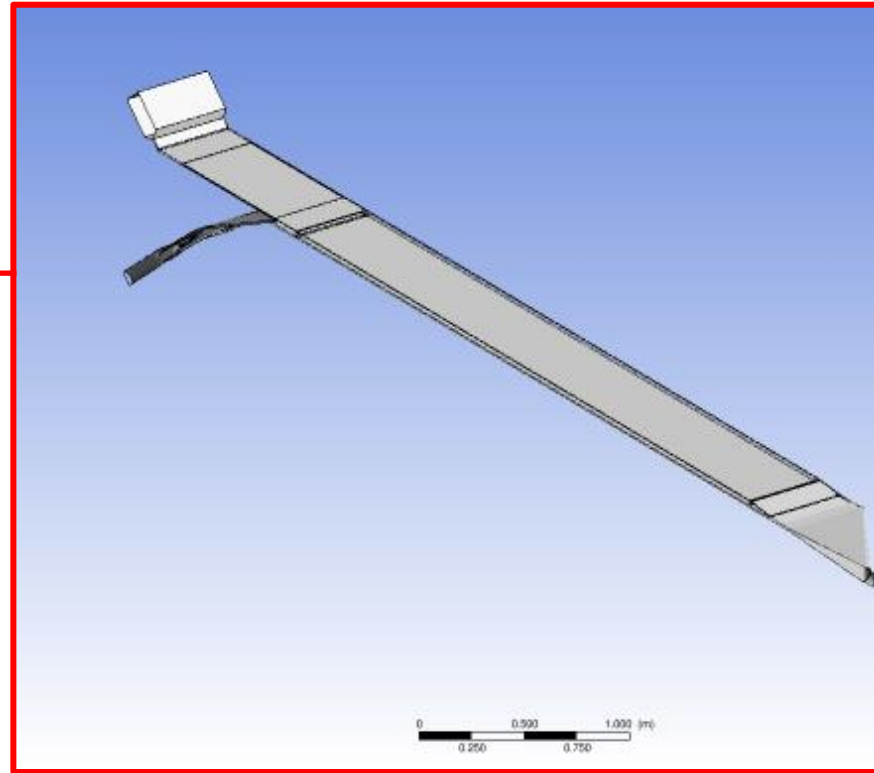


- Regarding the large amount of gas in the cell, an innovative design of the cell has to be defined to perform an efficient electrolysis process.
- The main challenges that need to be addressed:
 - 1) Define a cell design that allows a very short distance between anode and cathode to optimize the electrolysis efficiency.
 - 2) Deal with electrolyte and bubbles counterflows.
 - 3) Avoid bubbles accumulation in the cell especially close to the cathode and close to the anode (screening effect).
 - 4) Take advantage of the gas-lift effect (bubble motion gives momentum to the electrolyte that could be used).
 - 5) Perform an efficient gas / electrolyte separation to “send back” a pure electrolyte to the cell.

CFD models



Designed Installation



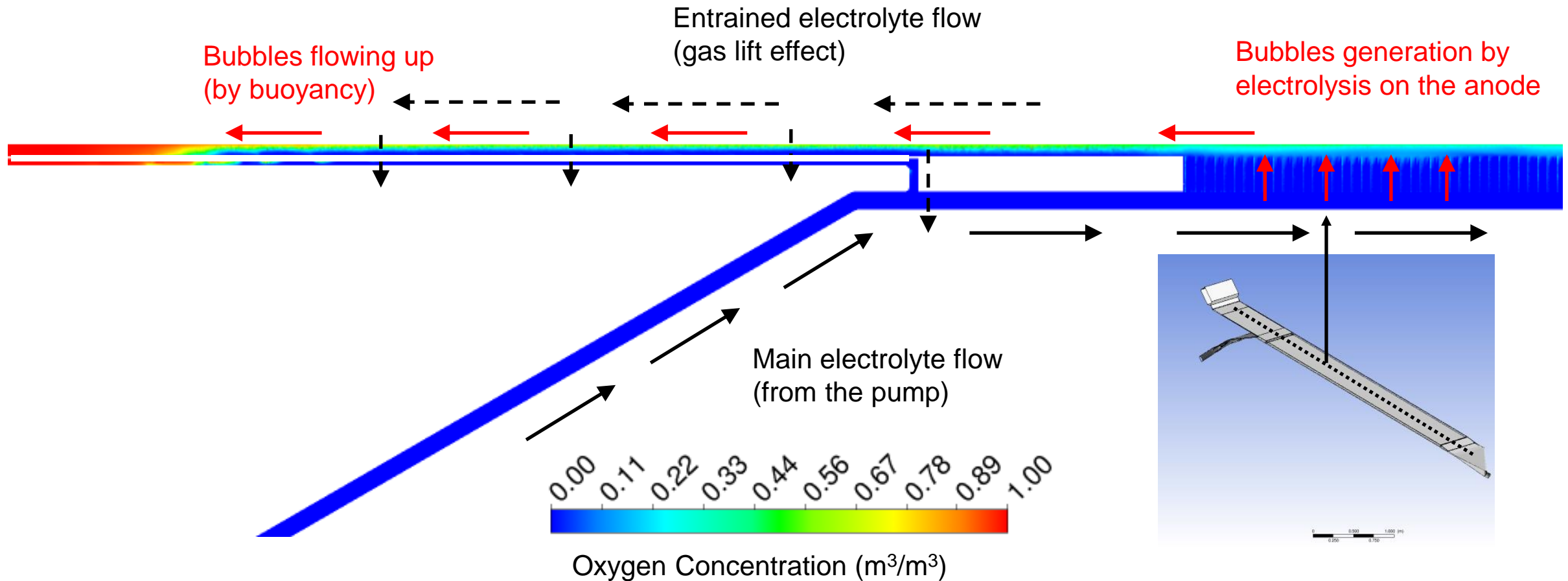
CFD models



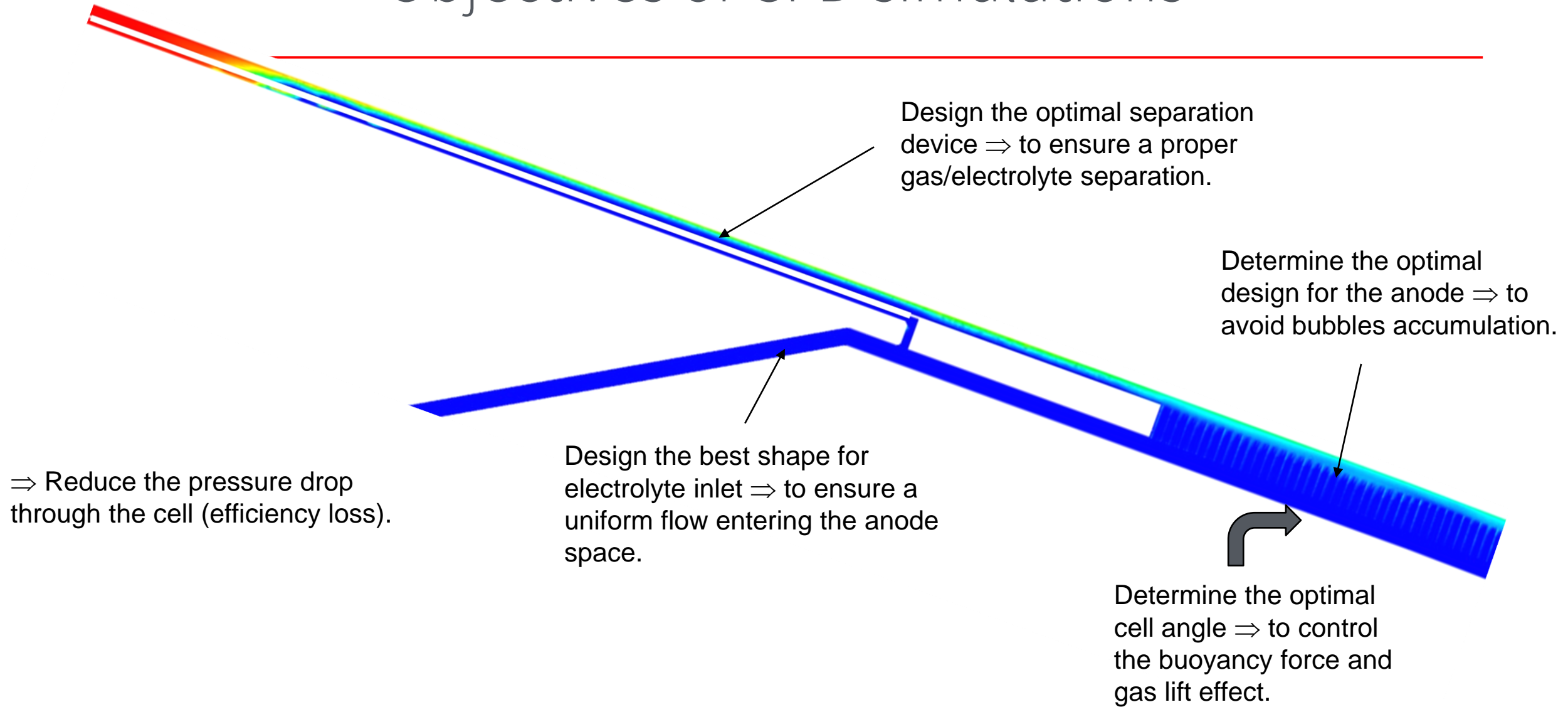
As manufactured

Flow phenomena

- Objective: define the most efficient design to drive bubbles out of the cells and drive back the entrained electrolyte to the main flow with an efficient separation.



Objectives of CFD simulations



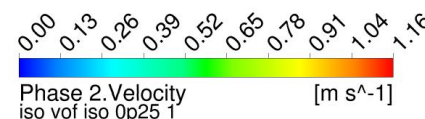
Main achievements by CFD (1)

Results assuming a 95% faradic efficiency

😊 Smooth electrolyte/gas counterflows with appropriate gas-lift effect.

😊 The proposed design avoids oxygen bubbles accumulation while keeping a short anode/cathode distance.

Oxygen bubbles equivalent surface

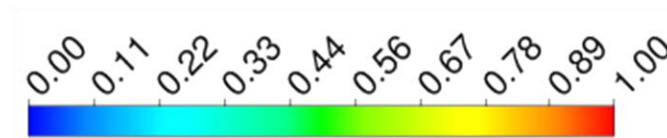


Bubbles Velocities (m/s)

Main achievements by CFD (2)

Results assuming a 95% faradic efficiency

😊 Efficient separation of gas and electrolyte.



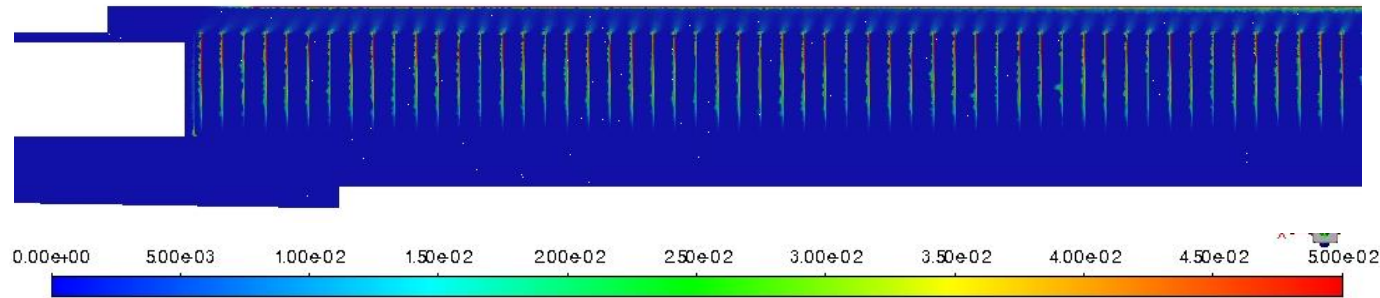
Oxygen Concentration (m^3/m^3)

Main achievements by CFD (3)

Results assuming a 70% faradic efficiency

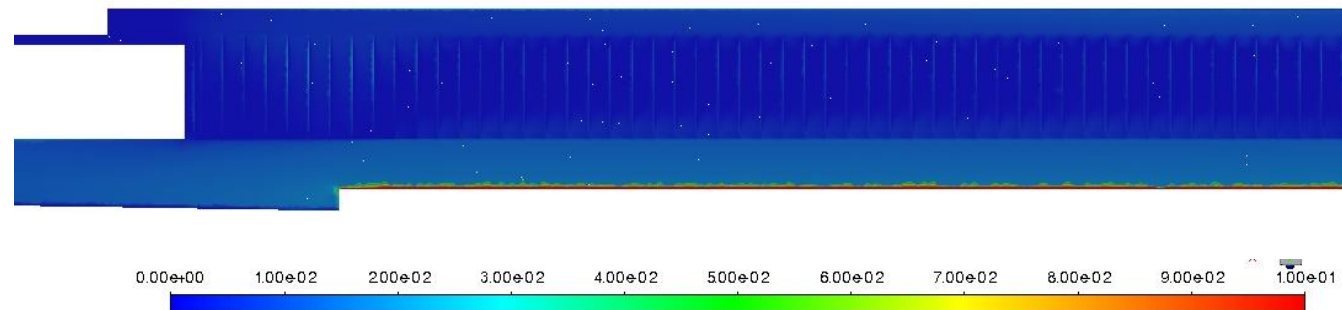
Zoom 1

O₂



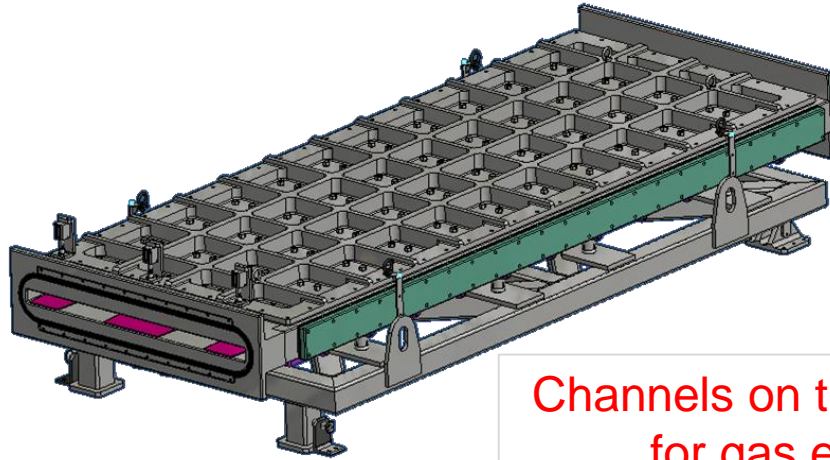
😊 Efficient separation of O₂ gas and electrolyte.

H₂



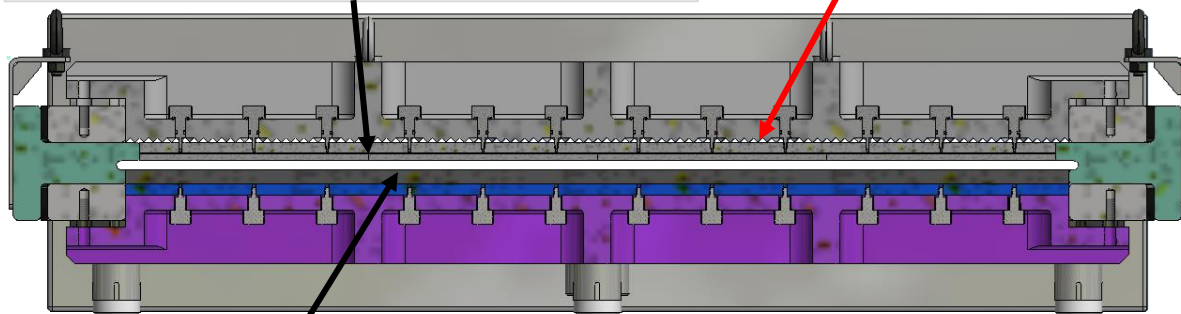
⊗ Some H₂ bubbles are entrained in the main flow ⇒ need to be fixed.

Electrowinning cell

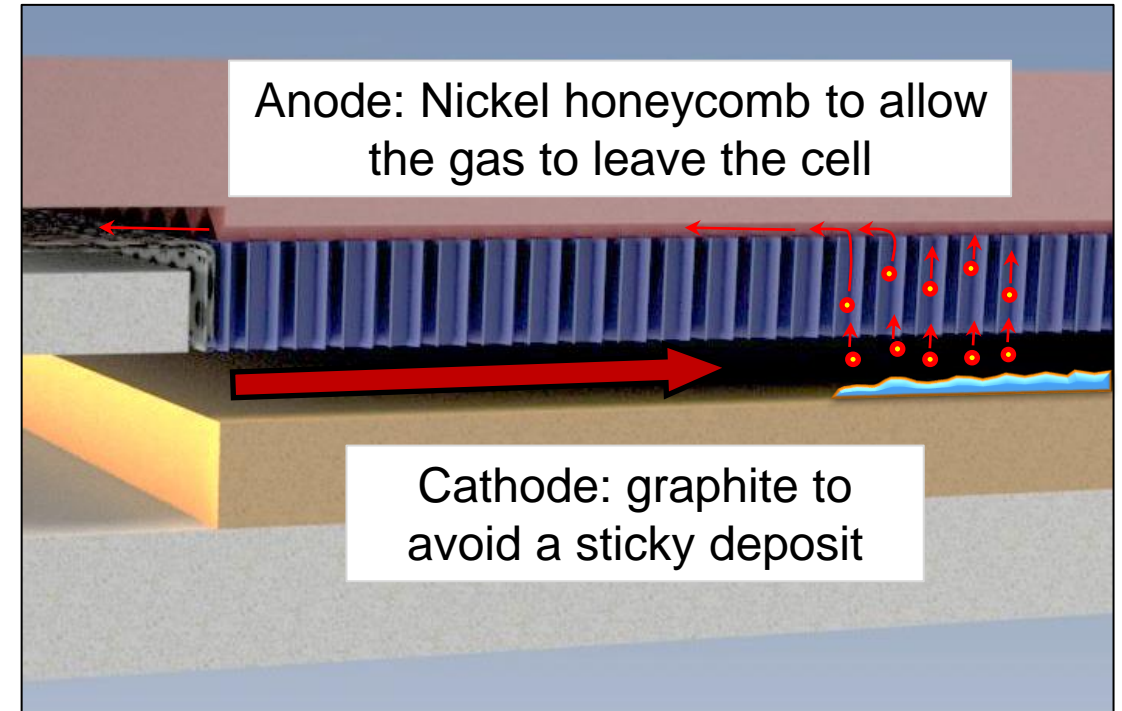


Channels on the anode cover
for gas evacuation

Anode: Nickel honeycomb



Cathode: graphite



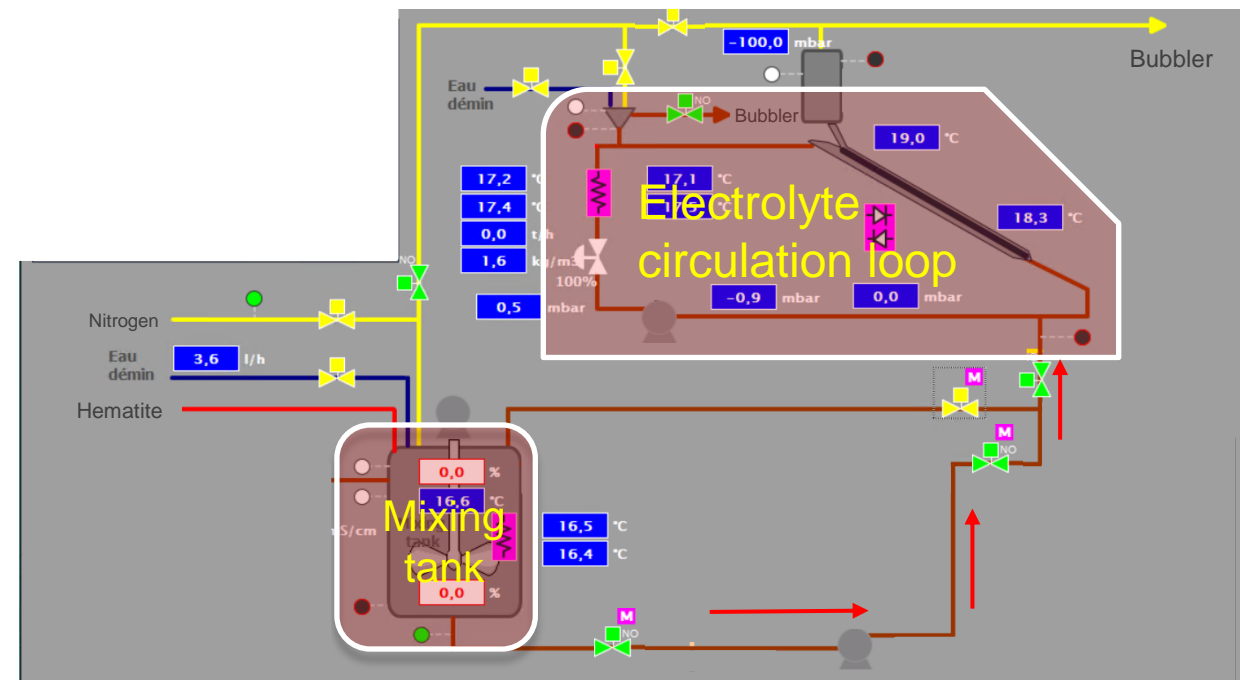
Anode: Nickel honeycomb to allow
the gas to leave the cell

Cathode: graphite to
avoid a sticky deposit

Pilot and operation

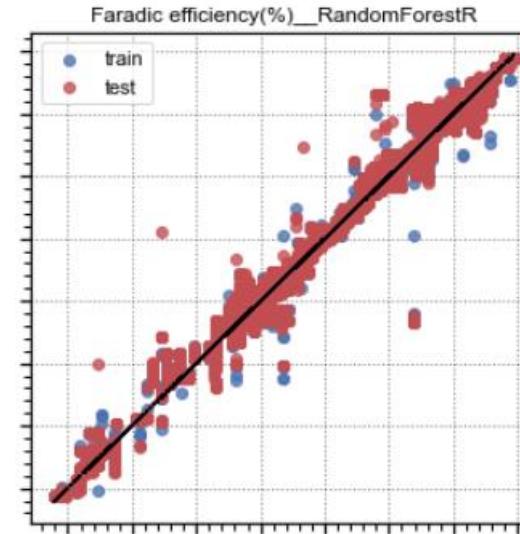
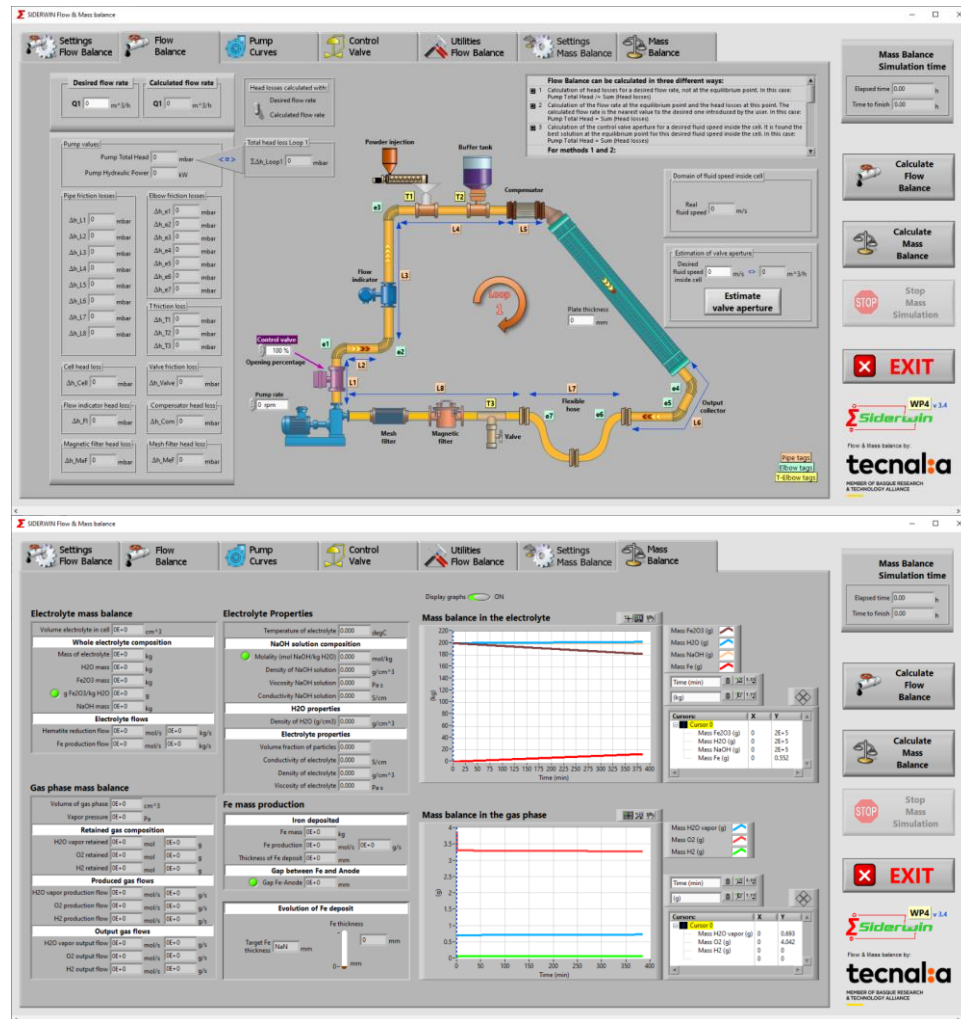


- There are four steps to preparing for pilot trials:
- (1): Preparation of the electrolyte in the mixing tank.
 - (2): Filling the closed loop with electrolyte.
 - (3): Circulation and heating of the electrolyte in the loop.
 - (4): Start of electrolysis.

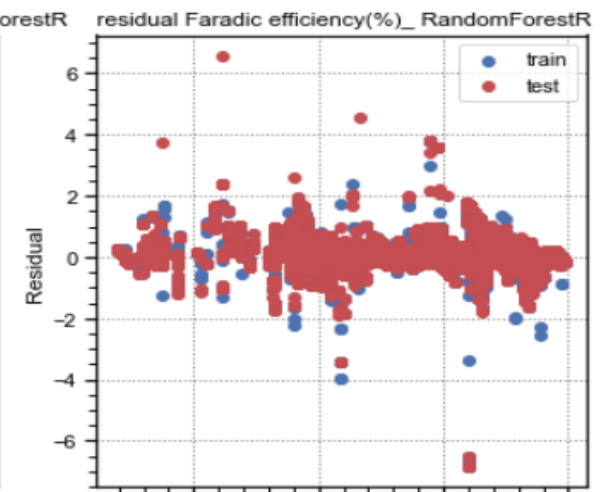
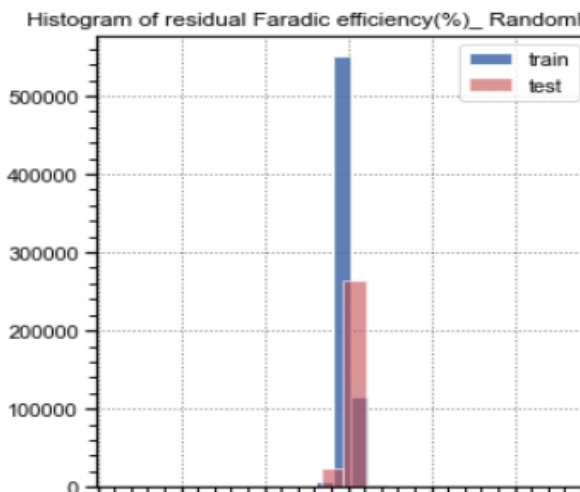


Pilot Cell Operation Simulation and Prediction

BURDINA – Mathematical Simulation Tool



Data Based Model
to calculate and optimise
the **Faradaic Efficiency**
of the Pilot Cell



The background of the slide is a blurred photograph of a modern office interior. In the center, the silhouettes of three people are visible as they stand and look out a large glass window. The window reflects the city skyline and a bright sky, suggesting a high-rise building. The overall lighting is dim, with the primary light source being the natural light coming through the window, which creates a silhouette effect on the people and a bright, hazy view of the city outside.

The key process parameters for an efficient
electrolysis of iron oxides into metallic iron

First parameter: good gas evacuation

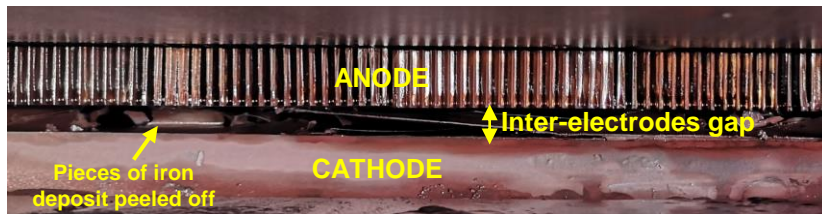
Trial in April 2022:

Very brittle deposit.

Iron produced: 2 kg.

Deposit thickness: from 0.1 to 0.2 mm.

Short circuits due to peeled-off deposit.



Trial in June 2022:

Deposit thickness: ~1 mm.

Iron produced: ~22 kg.

Plate less fragmented.



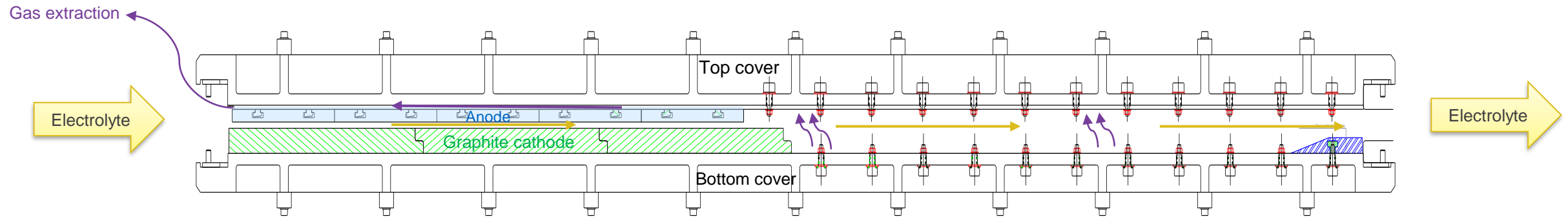
Immediate actions to improve the gas management:

- Lower hematite concentration.
- Lower electrolyte speed.

Further gas management was still needed.

First parameter: good gas evacuation

- Decreasing the amount of gas produced by reducing cathode size (1.25 m^2 instead of 2.75 m^2).
- Increasing the length available for gas extraction.



After this adjustment, a 1.25 m^2 iron plate had successfully been obtained.

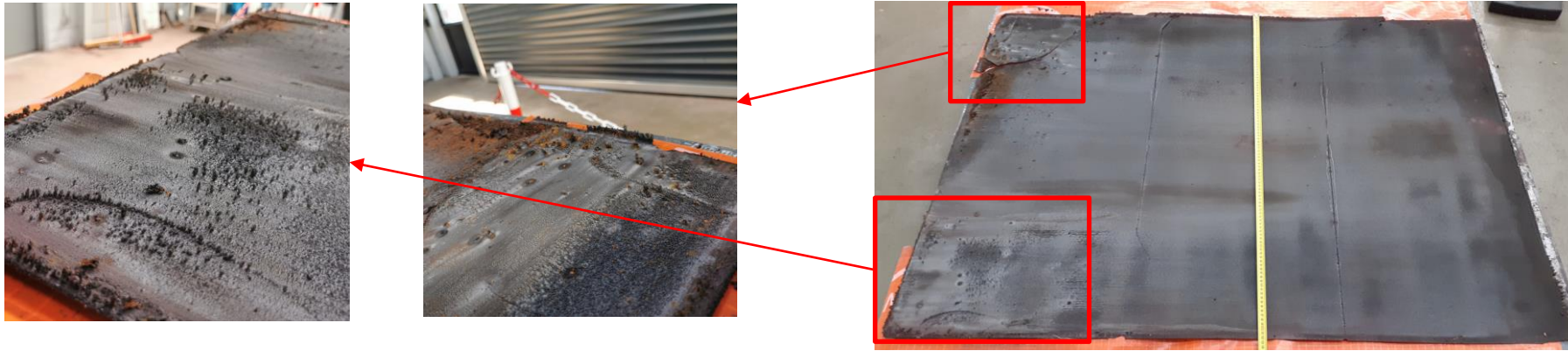
Trial in July 2022:

- Plate surface: 1.25 m^2 .
- Average deposit thickness: $\sim 1.5 \text{ mm}$.
- Weight: $\sim 15 \text{ kg}$.
- **Homogeneous** and **not fragmented** plate.
- Easy to separate from the cathode and to handle.



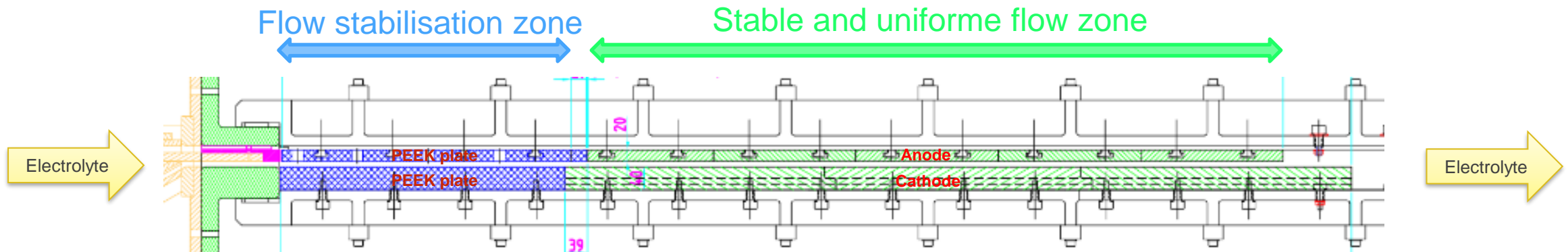
Second parameter: electrolyte flow uniformity

Formation of **dendrites** at the entrance of the electrolyte in the cell leading to electrical **short-circuits**.

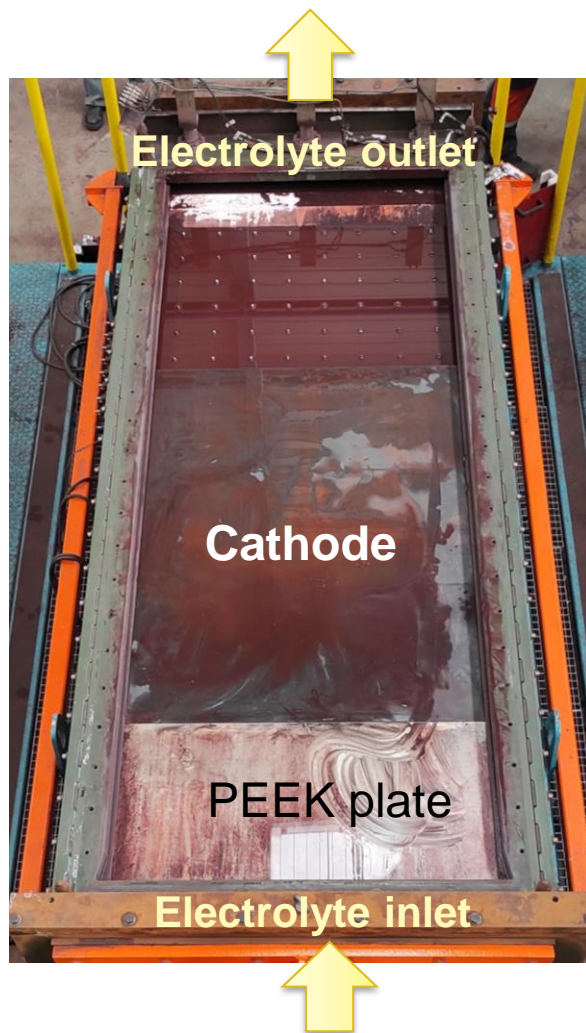


Improvement of electrolyte flow at the inlet of the cell:

- Installation of a PEEK insulating plate at the cell entrance/before the cathode.



Second parameter: electrolyte flow uniformity



Trial in September 2022:

Plate surface: 1.25 m².

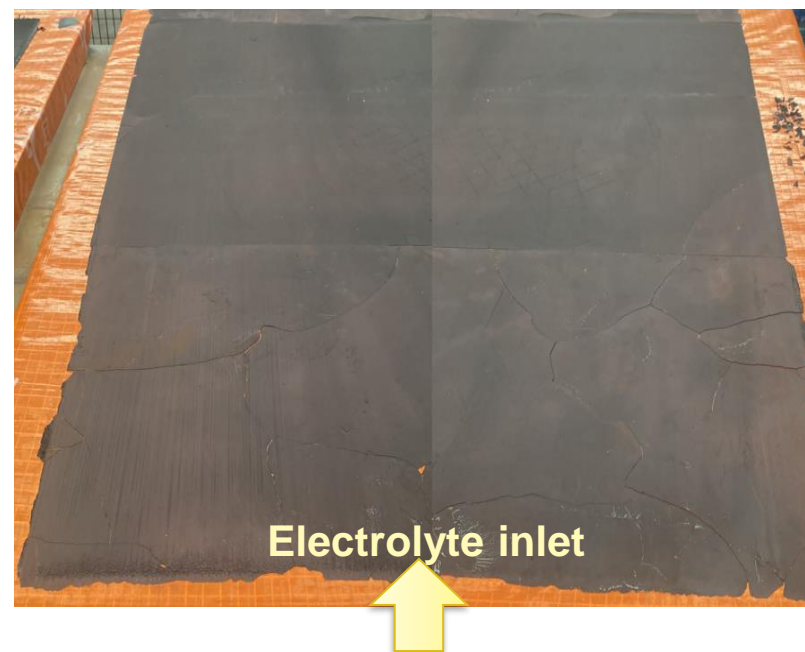
Iron produced: ~ 7.8 kg.

Average deposit thickness ~0.9 mm.

Homogeneous and **not fragmented** plate.

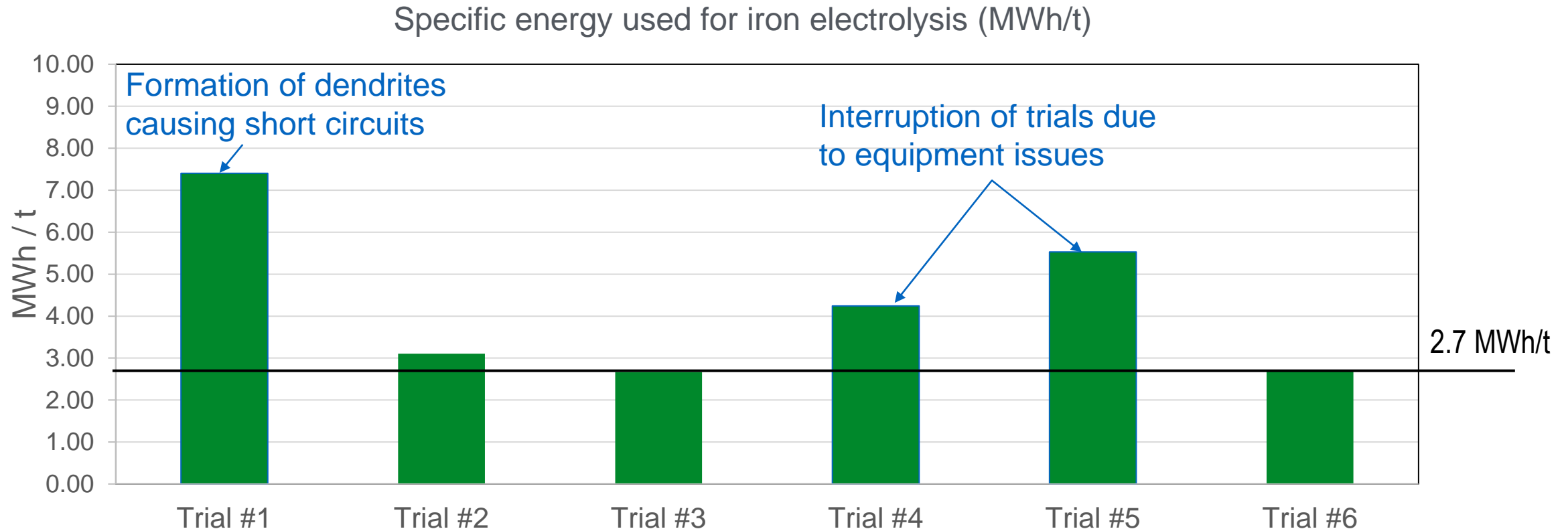
No dendrites formation.

The uniform electrolyte flow prevents the formation of dendrites.



Electrolysis cell energy consumption

Electrolysis cell energy consumption




The **specific energy of 2.7 MWh/t** is **achievable** in **stable conditions** (Electrical, electrolyte flow, gas evacuation...)

The background of the slide is a blurred photograph of a modern office interior. Several people are visible as dark silhouettes against a bright, hazy light coming from large windows. The people appear to be in motion, with some standing in groups and others walking. The floor is highly reflective, creating clear mirror images of the people and the light from the windows. The overall color palette is dominated by dark blues, greys, and a warm, golden-yellow glow from the light source.

Conclusions

Summary

- A comprehensive method has been used to design the optimal cell and identify the potential bottlenecks.
- A coherent iron plate of 1,25 m² is achievable with an easy separation from the graphite cathode.
- The key process parameters for an efficient electrolysis of iron oxides into metallic iron:
 - 1) Good gas evacuation.
 - 2) Uniformity of the electrolyte flow.
- As for the cell, the specific energy consumption of 2.7 MWh/t is achievable under stable conditions (electrical, electrolyte flow, gas evacuation...).

The background is a dark, artistic composition of technical drawings and mechanical parts. It includes various engineering sketches, cross-sections, and detailed views of components like a bearing, a lens, and a small metal bracket. The drawings are overlaid on a dark, textured surface, possibly wood or a dark cloth, creating a professional and technical atmosphere.

Thank you
for your attention

Questions?



Development of new methodologies for Industrial
CO₂-free steel production by electro-winning

The flexible potential of SIDERWIN process for the future European power system

Morgan Barberousse – EDF R&D
Webinar March 23rd 2023

Key idea / Challenge

1

Analyze the impact of a ΣIDERWIN industrial development in the future European electricity system (2050)

Focus on:



Energy consumption

Costs and benefits for the power system



Flexibility potential

Carbon emissions reduction

2

Check the ability of the pilote to operate in an on-demand mode, so to offer a real flexible potential for the system

Focus on:

Functional analysis and load curve

Test of interruption and modulation

Responsiveness and duration

Process and quality impacts

1. Integration into the future European electricity system

LAYOUT

Step 1: input data collection about the evolution of the future European electricity system and the steel industry.

Step 2: modelling of the future European electricity system (connections, electricity mix, demand, ...).

Step 3: parametric assesement (plants location, climate variations, fuel prices, CO₂ price, plant outages, ...).

Step 4: behaviour of the power system with SIDERWIN and costs and benefits evaluation.



UE Reference scenario.

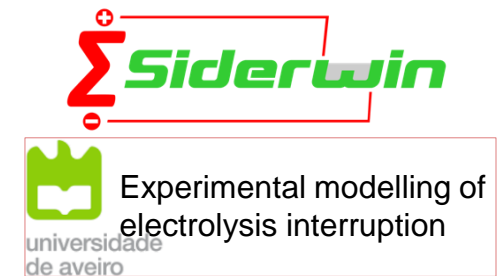
RES chronicles.



Energy and carbon intensity hypothesis.



Steel industry development Hypothesis.



SIDERWIN specifications and development Hypothesis.

1. Integration into the future European electricity system

ADAPTATION OF THE 2050 POWER SYSTEM MODEL TO MEET ADDITIONAL SIDERWIN DEMAND:

Additional SIDERWIN demand:

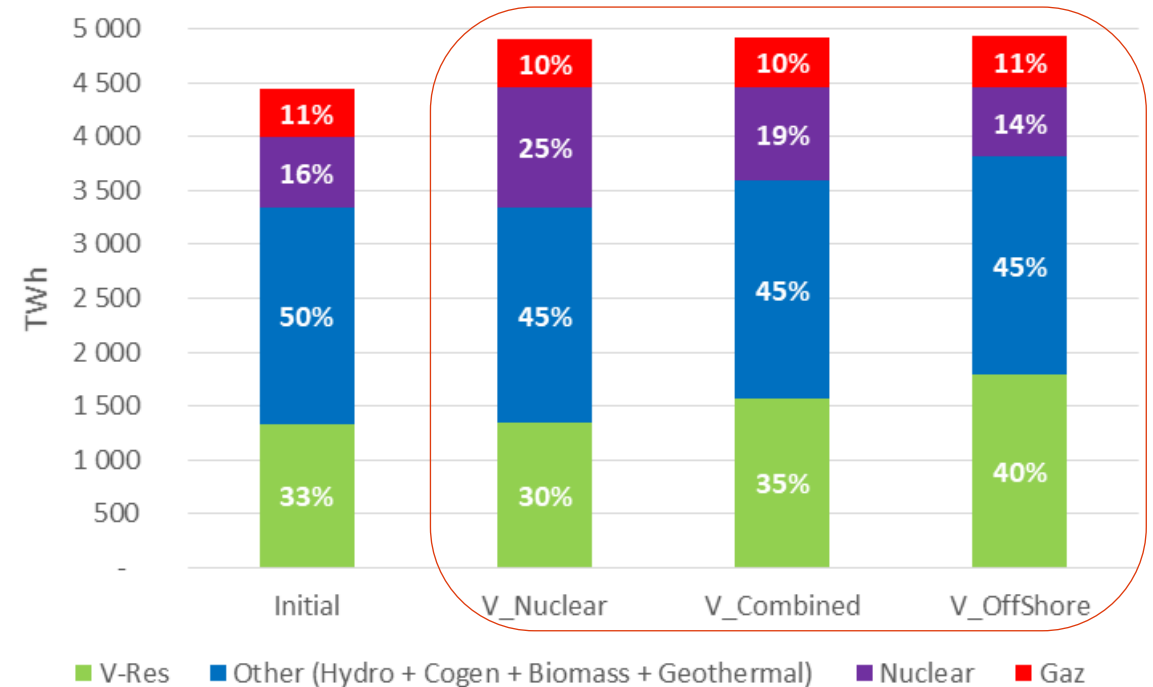
471 TWh per year in 2050

(+ 12% in average of EU electricity consumption)

Lever: only low carbon electricity sources.

Different scenarios:

- 1/ additional 100% nuclear power.
- 2/ additional 50% nuclear and 50% offshore wind.
- 3/ additional 100% offshore wind.

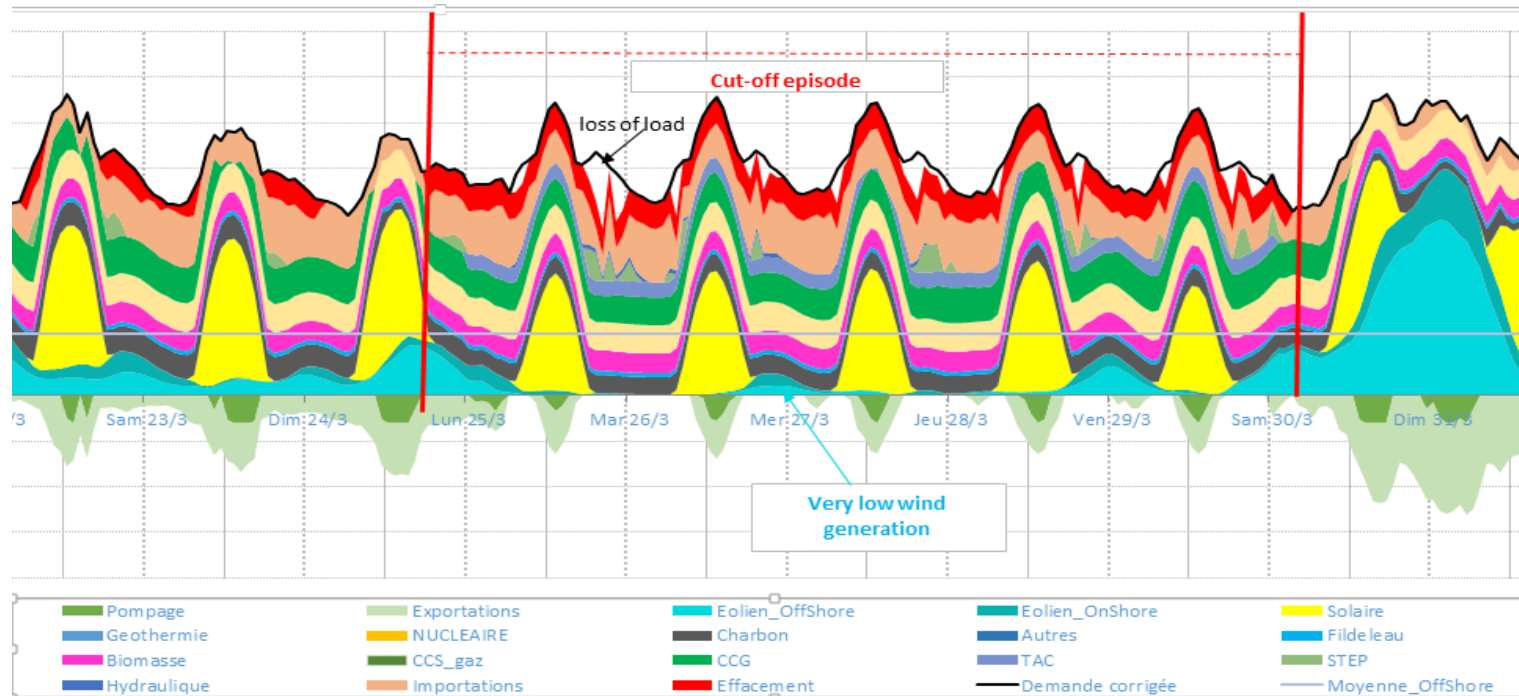


Evolution of the generation mix in Europe

1. Integration into the future European electricity system

CUT-OFF CAPACITY:

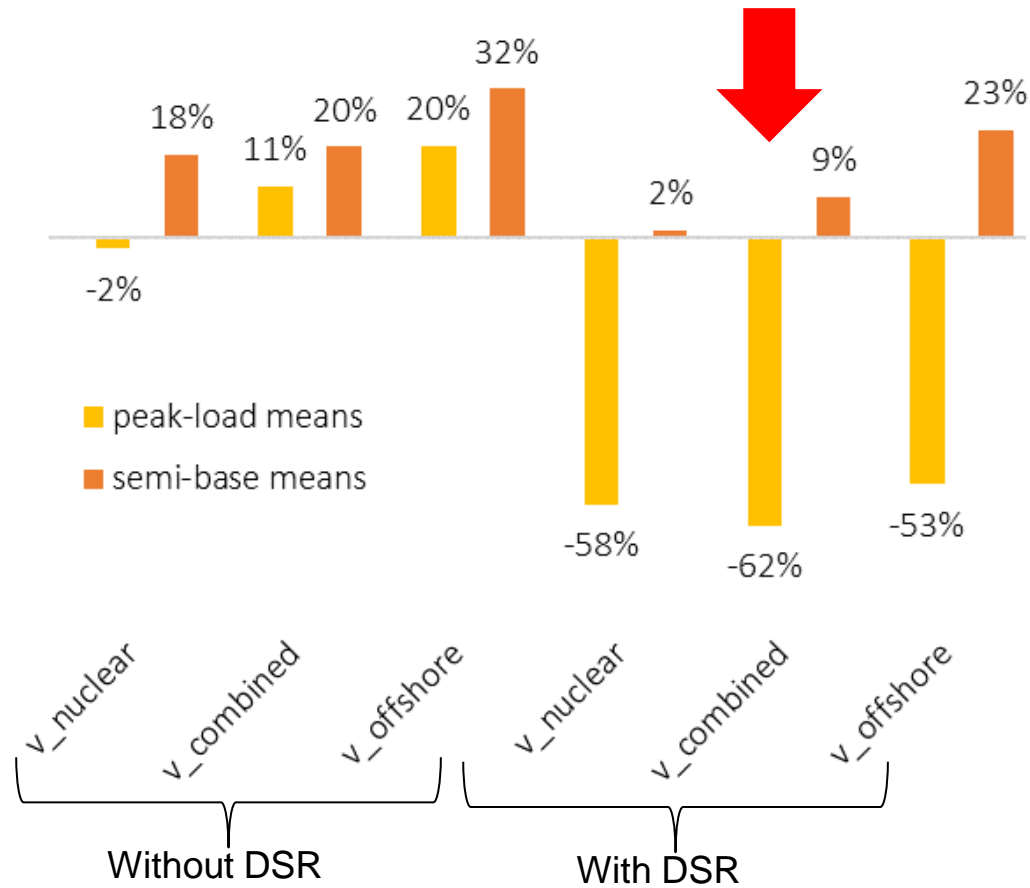
SIDERWIN cut-off capacity of 39 GW (11 -13 TWh)



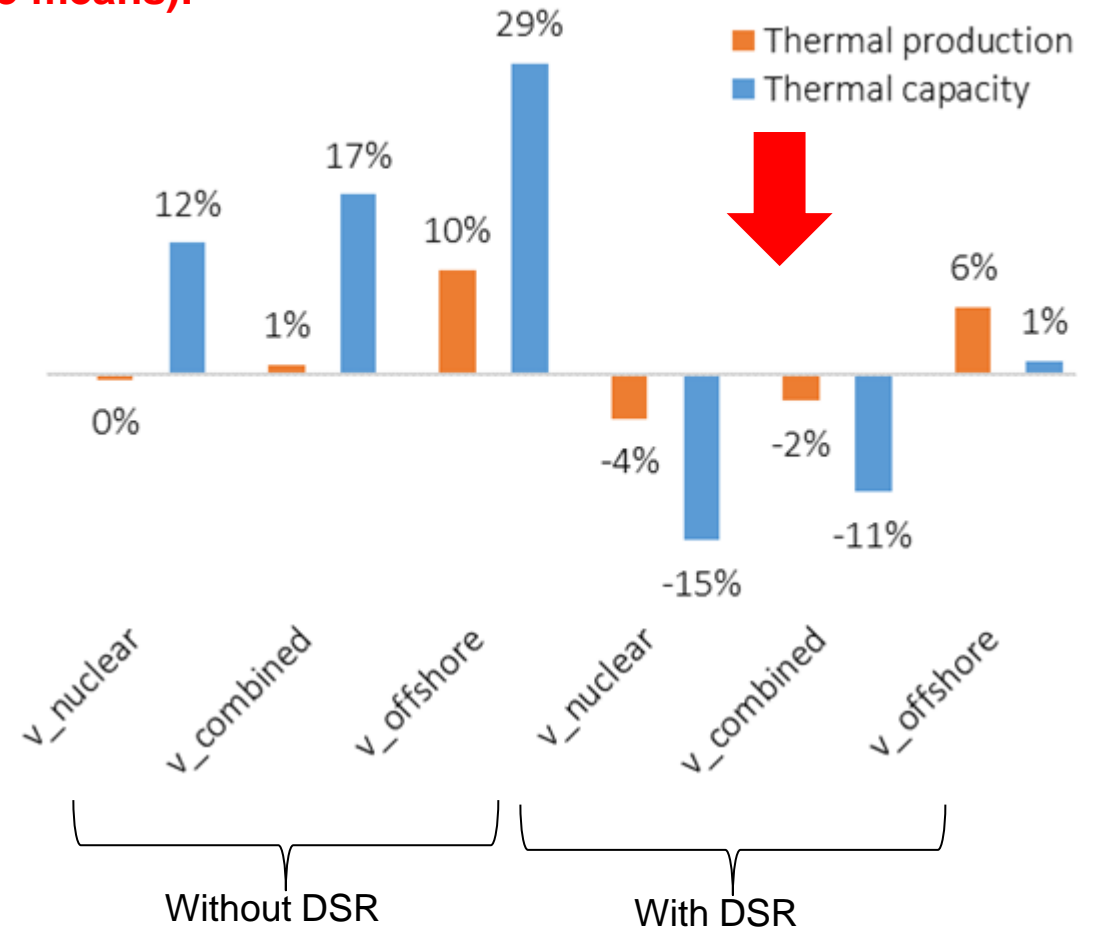
Example of flexibility : Solicitation of the different generation technologies to meet demand, during a week with very low wind and high demand – Germany, Offshore Dataset.

1. Integration into the future European electricity system

IMPACT ON THE THERMAL PARK (peak-load and semi-base means):



Thermal capacities variations by means



Thermal production and capacities variations

1. Integration into the future European electricity system

MAIN RESULTS / KEY MESSAGES:

The deep decarbonation of steel industry enabled by ΣIDERWIN is not jeopardized by the impact on power system.

- The European power system is able to meet the additional ΣIDERWIN demand (+471TWh/y in 2050) with carbon-free means.
- Despite a strong increase in electricity demand, **the impact on CO₂ emissions of the European power system is very low** (even positive in certain scenarios) and depends on the choice of technologies used to meet the additional demand of ΣIDERWIN.
- In all scenarios, **the carbon intensity of electricity generation (g CO₂/kWh) decreases**.
- The flexibility offered by ΣIDERWIN allows for additional CO₂ savings, by replacing a large part of the peaking OCGT plants.

1. Integration into the future European electricity system

MAIN RESULTS / KEY MESSAGES:

Flexibility offered by ΣIDERWIN: A real need for the power system that finds an economic place in the contribution to the supply-demand balance.

- ΣIDERWIN should offer a **great flexibility capacity, of up to 39 GW in a European scale**, with great responsiveness and without duration or repeatability constraints.
- **This flexibility represents a real asset for the European Power System**: it could contribute to the balance of the power system.
 - A replacement of peak-load means (OCGT*): 80% of generation.
 - A reduction in CO₂ direct emissions: 6 Mt of direct CO₂ emissions avoided.
 - Financial gains (mainly related to investment costs avoided) : several B€/yr for the whole of Europe.

1. Integration into the future European electricity system

DELIVERABLES:



PROJECT: SIDERWIN
Deliverable:
D7.2

Title:
Framework of the techno-economic and environmental assessment
Process integration with RES

Date: 30th September 2020

Version: 1.0

Website: N/A

6-063-20 Barberousse

Electrification of primary steel production based on SIDERWIN process: simulation on the European power system in 2050

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Abstract

The growing steel industry represents 4% of the total European carbon emissions (EU27). The current coal based blast furnace process used to make primary steel has been widely optimized over the past decades to become as efficient as possible. Because of limited opportunities for further enhancements in the existing process, the decarbonisation of the primary steel industry requires a breakthrough innovative technology.

At the same time, Europe aims to be climate neutral by 2050 and have net-zero greenhouse gas emissions. To contribute towards reaching this goal, the European H2020 – SIDERWIN project aims to develop a breakthrough process for the primary steel production, based on electrolysis, as a low carbon alternative to the current blast furnace.

As it is a flexible and electricity intensive technology, SIDERWIN's industrial development in Europe may play a significant role in the European power system in terms of electricity demand, and demand-side response capacity. This paper focuses on the SIDERWIN technology and its contribution to the future European power system. Based on projections of the steel demand in 2050 and the specific energy consumption of this technology, a prospective scenario is simulated in order to assess SIDERWIN's contribution in production and demand balancing, and the benefits to the power system. The methodology for this study and the simulated scenario are presented, and the potential reduction of the CO₂ emissions related the flexibility of the SIDERWIN technology is assessed. Further steps into the calculation of this potential and the simulation of different scenarios are finally discussed.

Introduction

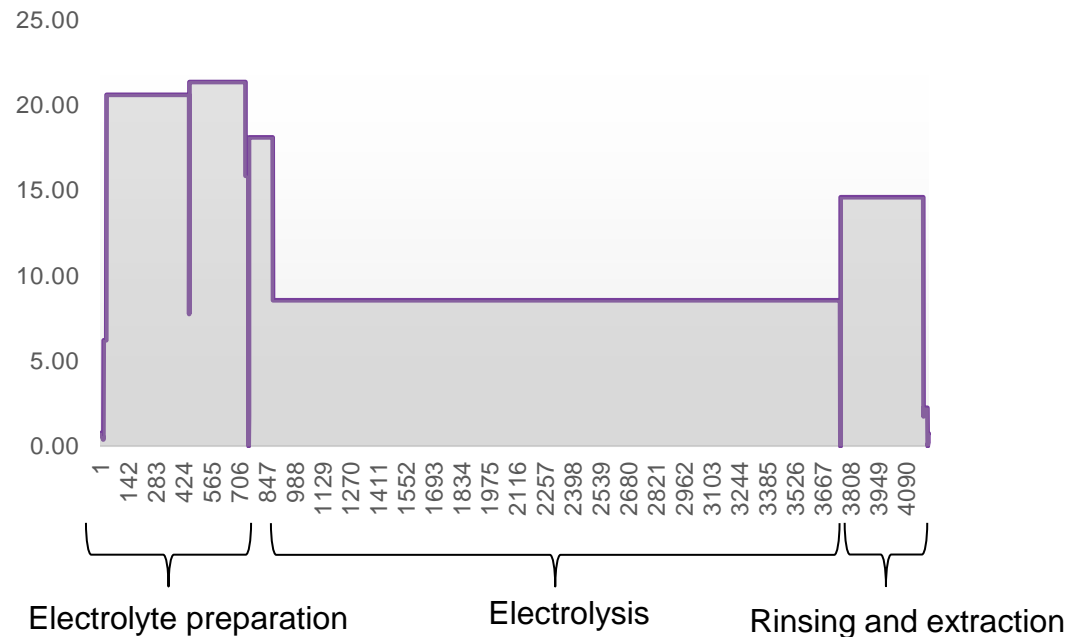
Europe aims to be climate neutral by 2050 and have net-zero greenhouse gas emissions. This objective is at the heart of the European Green Deal and the global climate commitment under the Paris Agreement. This means that all sectors of the economy will have to be climate neutral from the power sector to the industry, mobility, buildings, agriculture and forestry. The power sector is at the forefront of the reduction of carbon emissions with the phase-out of carbon-intensive coal production and the development of solar and wind renewables alongside existing

2. Validation of the ability to operate in an on-demand mode

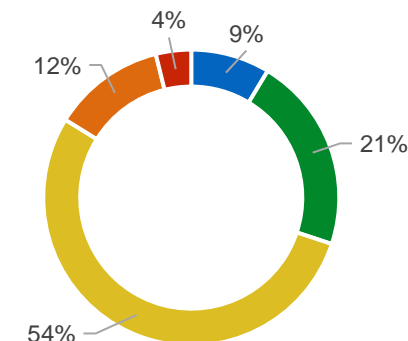
OBJECTIVES:

- 1/ Analyse the electricity demand for each step of a production cycle, and the options to balance the load curve.
- 2/ Check the ability to modulate or interrupt the electricity consumption of the main consumers (responsiveness, duration, frequency, behaviour and impact on the product quality).

Theoretical load-curve based on installed powers



Theoretical electricity consumption of the pilote

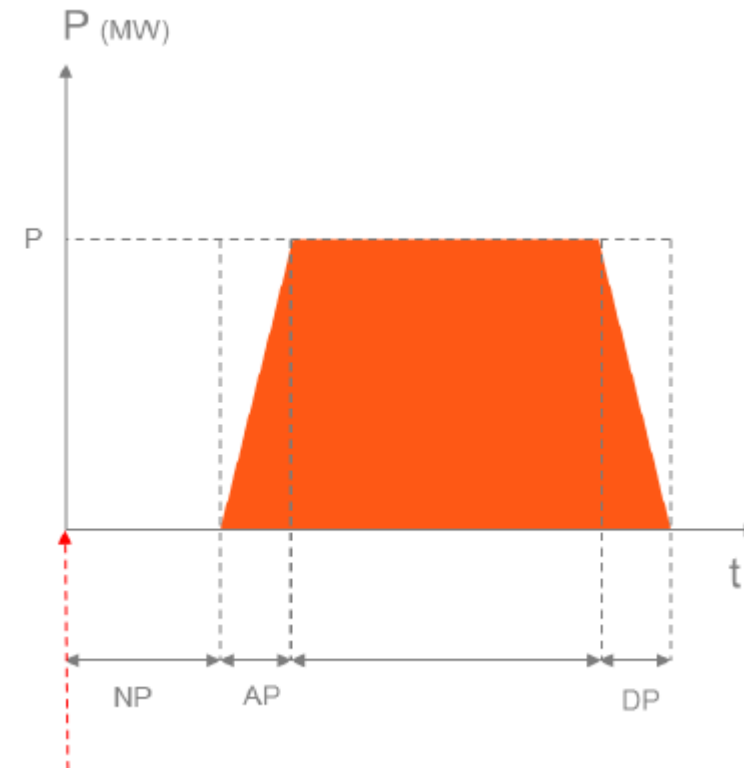


■ Electrolyte preparation ■ Heating of the loop ■ Electrolysis ■ Rinsing ■ Instrumentation and valves

2. Validation of the ability to operate in an on-demand mode

TEST PROCEDURE:

1. **Description of each sequence (chronology, equipments, power, duration).**
2. **Adaptation theory / practice.**
Security adaptations (feedback).
Optimisation of a production cycle.
Equipement évolutions.
3. **Load curve measurement.**
4. **Cut off / modulation tests for each sequence.**
5. **Data collection and analyse.**
Cut off / modulation reactivity.
Impact of an interruption on the process.
Impact of a long interruption.
Rebound effect (heating).



2. Validation of the ability to operate in an on-demand mode

KEY MESSAGE:

Flexibility potential validated:
good reactivity ($<1s$) and no duration constraint (except rebound effect for heating sequences).

Possibility to operate on the most profitable DSR markets.



Thank you

EDF main collaborators:

Matthildi Apostolou

Morgan BARBEROUSSE

Caroline BONO

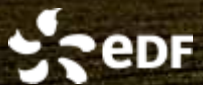
Anne DEBREGEAS

H2020 ΣIDERWIN project


Research institutes:

EDF R&D Division, France

This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 768788".



"This study reflects only the authors' views and the Commission is not responsible for any use that may be made of the information contained therein"

The background is a dark, artistic composition of technical drawings and mechanical parts. It includes various engineering sketches, cross-sections, and detailed views of components like a bearing, a lens, and a small metal bracket. The drawings are overlaid on a dark, textured surface, possibly wood or a dark cloth, creating a professional and technical atmosphere.

Thank you
for your attention

Questions?



Development of new methodologies **S** for In**D**ustrial
CO₂-fre**E** steel p**R**oduction by electro**WIN**ning

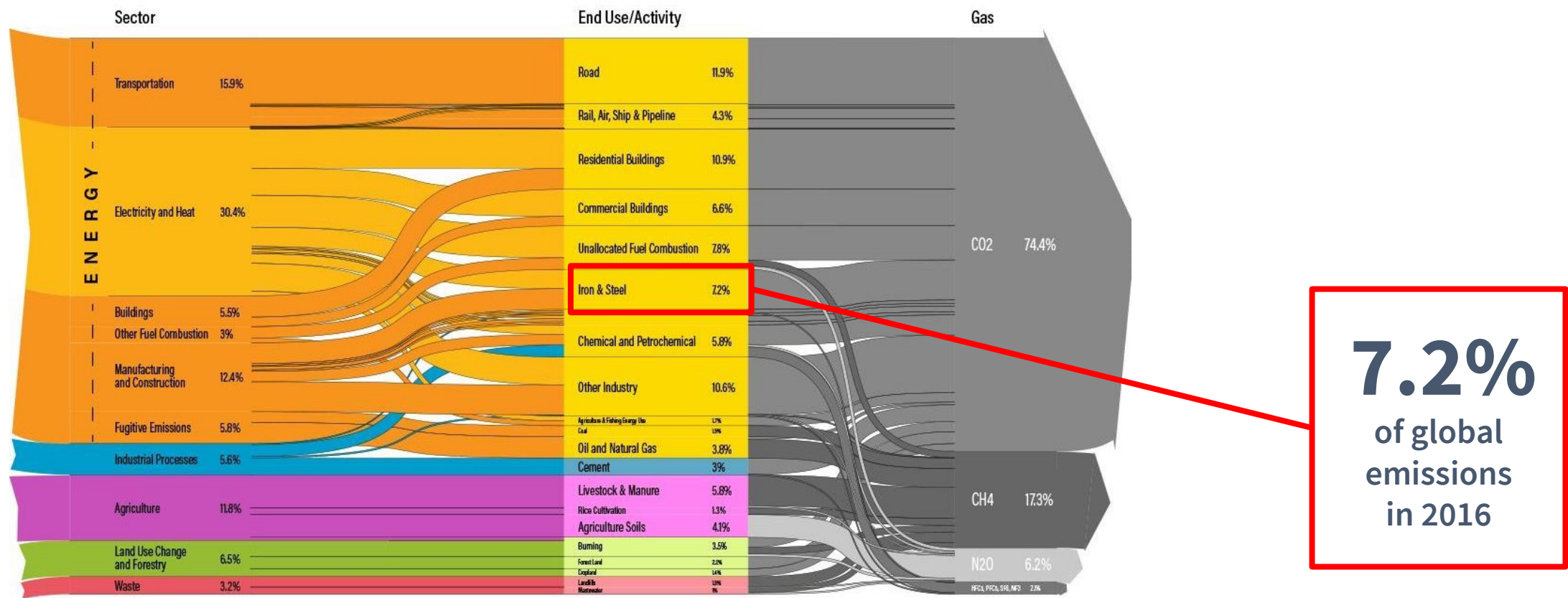
What is the environmental impact and cost of steel decarbonization with SIDERWIN?

Roland Kahmann – RECOY
Webinar March 23rd 2023

The background is a dark, artistic composition of technical drawings and mechanical parts. It features several sheets of paper with detailed engineering sketches, including cross-sections of shafts, gears, and structural components. Scattered across the papers are various mechanical parts: a ball bearing, a small gear, a metal bracket, and a cylindrical component. The overall aesthetic is industrial and precise, with a focus on engineering and design.

The decarbonisation potential of SIDERWIN

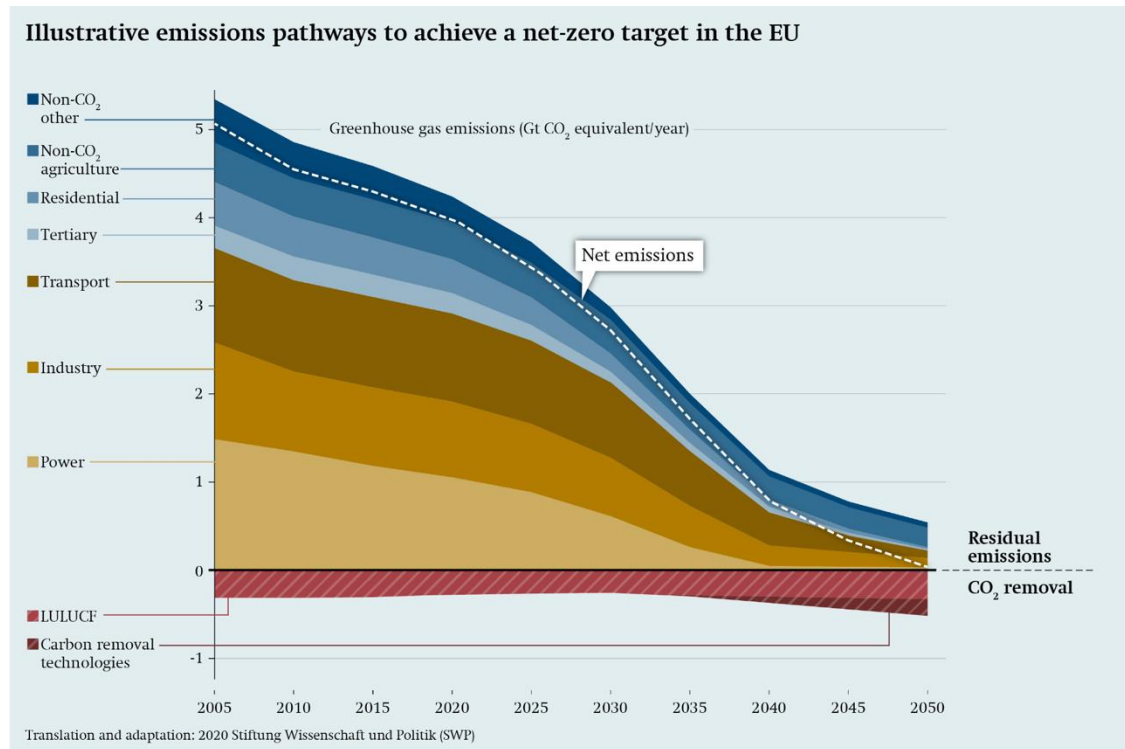
The steel industry is a major contributor of the global GHG emissions



7.2%
of global
emissions
in 2016

Source: WRI, 2016

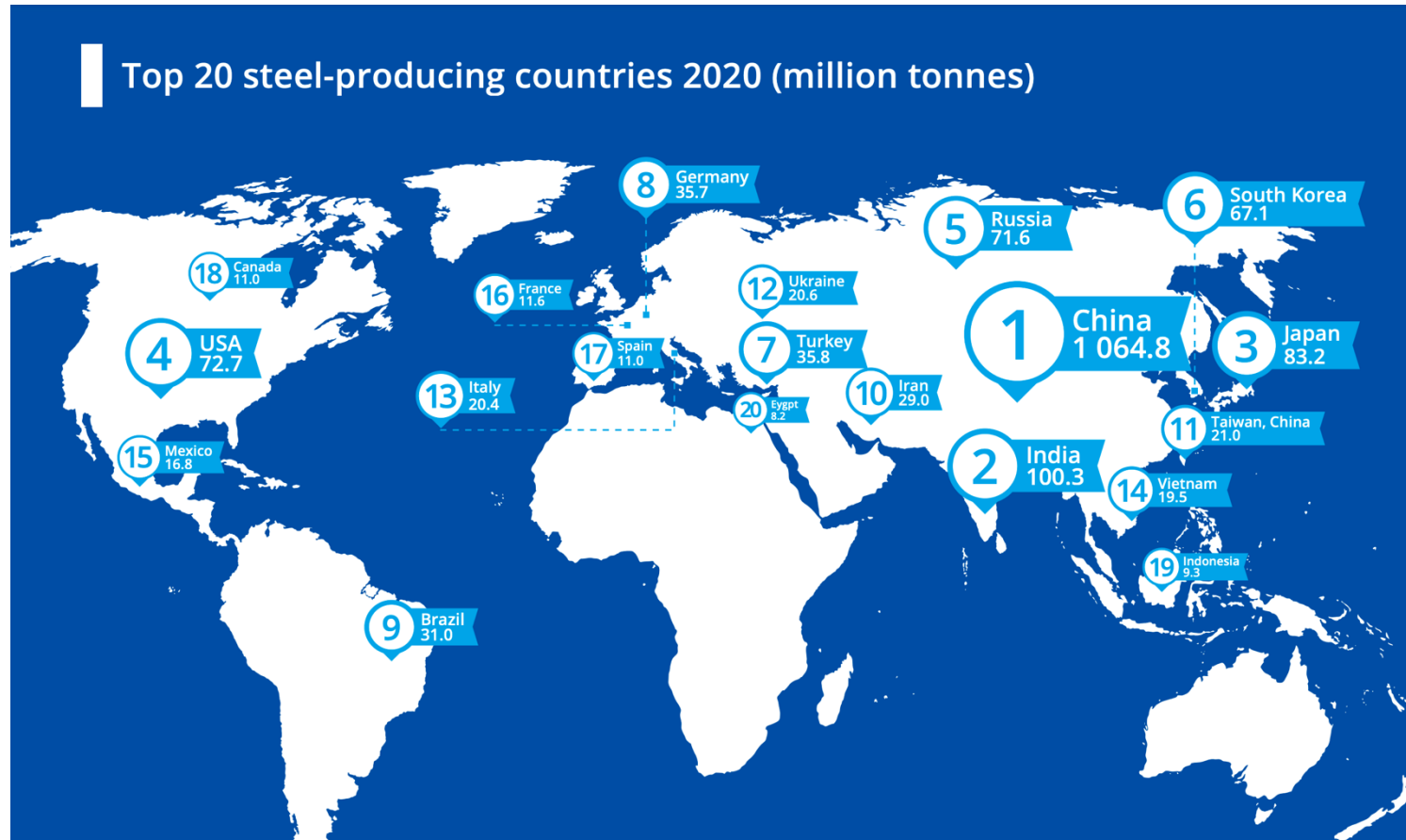
A net-zero target in the EU for all sectors



Source: World Economic Forum, adapted from the SWP, 2020.

- The EU Net 0 Roadmap targets a 30% reduction in 2030 compared to 2018, and being close to neutrality by 2050.
- The steel sector has its part to play, and can follow this reduction pathway with the proper policies and technologies (EUROFER, [A Green Deal on Steel](#)).
- The European Green Deal sets the objective of creating new markets for climate neutral and circular products, such as steel, cement and basic chemicals. (European Commission, [A New Industrial Strategy for Europe](#))

Europe can lead the way to the steel sector's decarbonisation



- 10% of steel is produced in Europe in 2020 – out of 1878 million tons worldwide.
- By developing innovative technologies to decarbonise its steel sector, Europe can inspire other steel-producing countries.

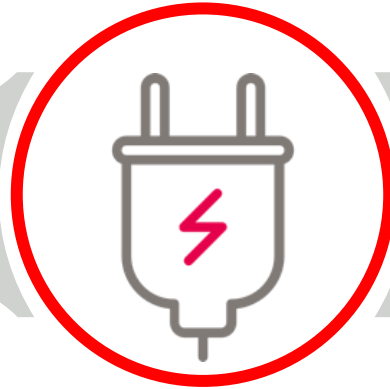
Source: Worldsteel, 2020

Carbon footprint emissions classification



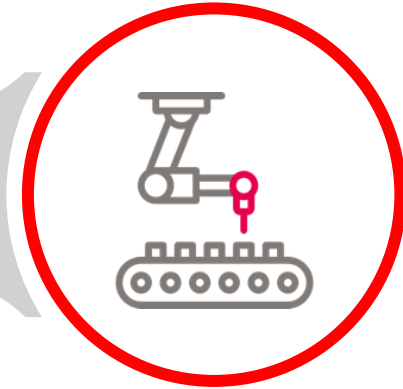
SCOPE 1 EMISSIONS **Direct emissions**

By electrifying steel production, the SIDERWIN technology could help reduce the direct emissions of the steel sectors.



SCOPE 2 EMISSIONS **From purchased power**

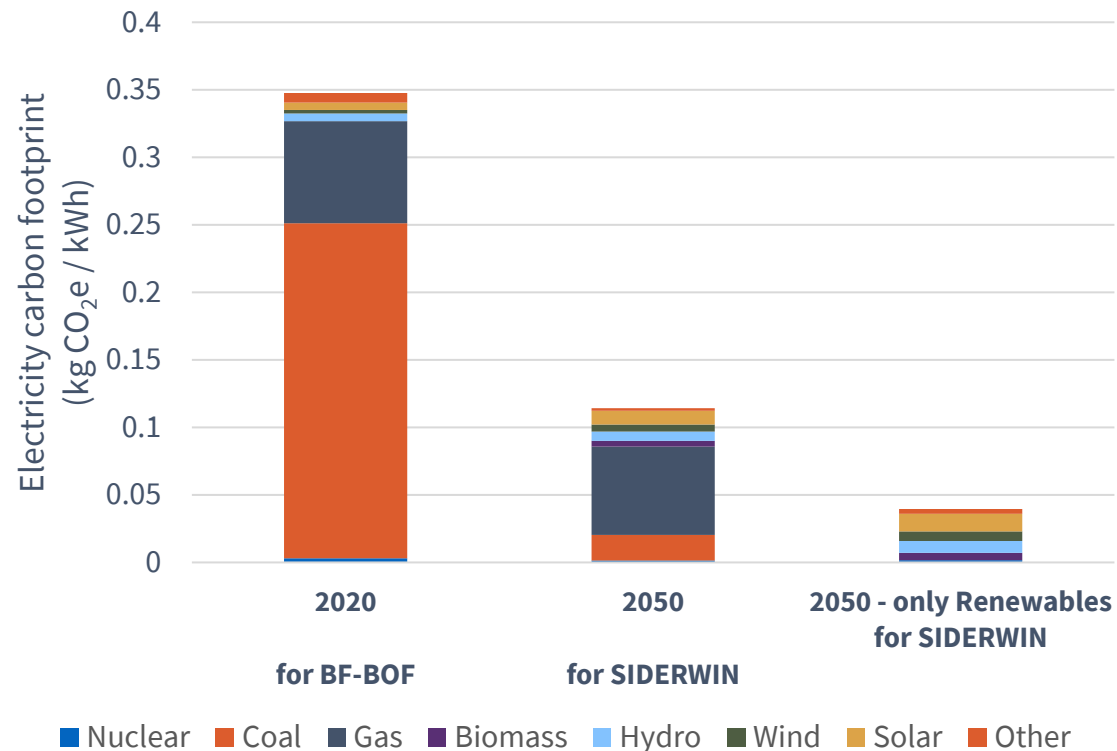
The ongoing decarbonisation of the electricity sector in Europe will drive the emissions of electrified steel production down.



SCOPE 3 EMISSIONS **From the value chain**

High carbon-footprint inputs such as lime will be reduced by the SIDERWIN technology, reducing the emissions caused by steel's upstream value chain.

Electricity Mix Scenarios



Several scenarios on the electricity mix were assessed to capture the potential of SIDERWIN:



2020*:

an average electricity mix « as is » in Europe



2050*:

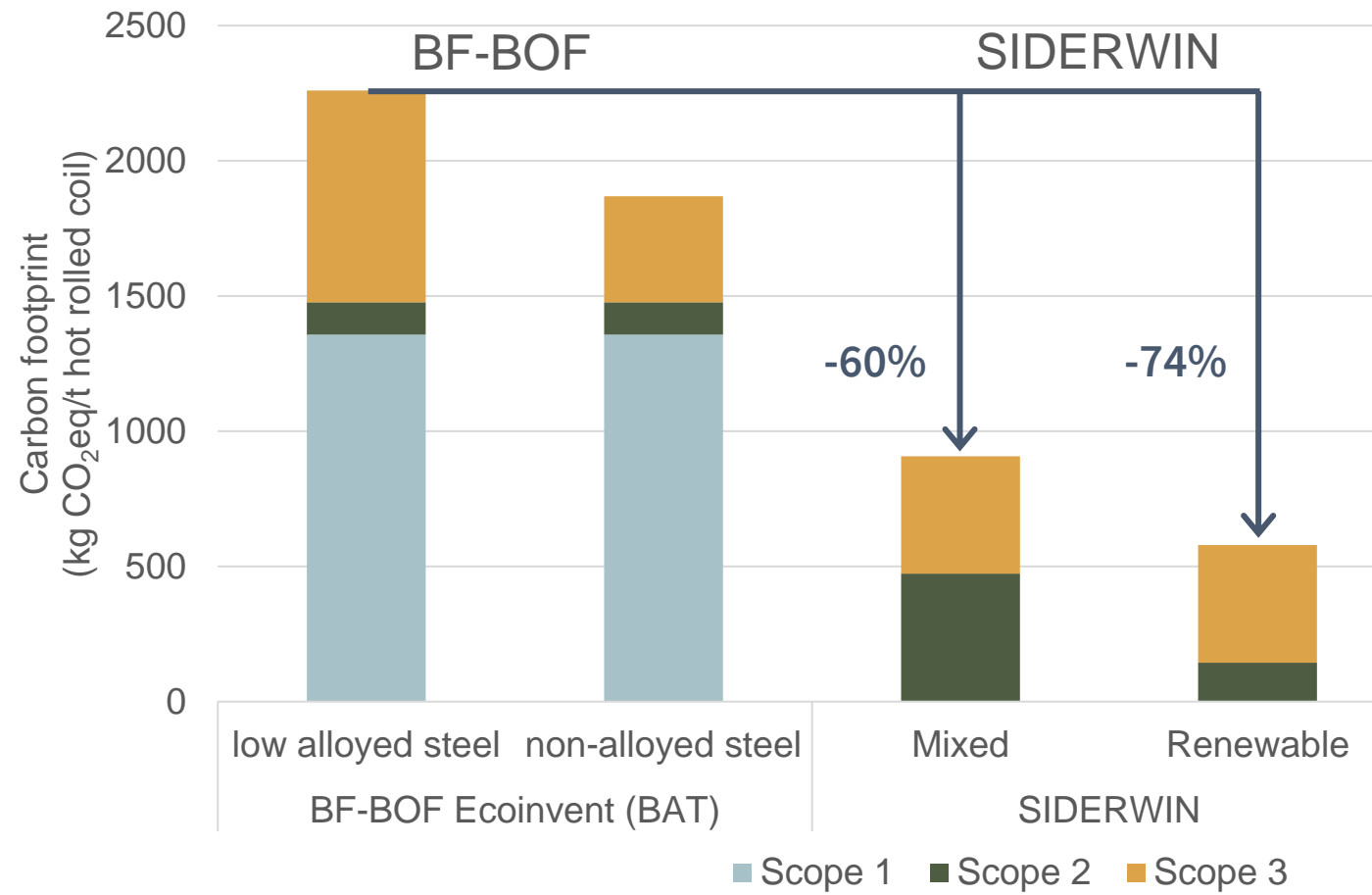
the electricity mix in 2050 according to projections developed by EDF in D7.2



2050 – only renewables:

a 100% renewable mix

Carbon Footprint of SIDERWIN compared to the Reference Technology (BF-BOF)



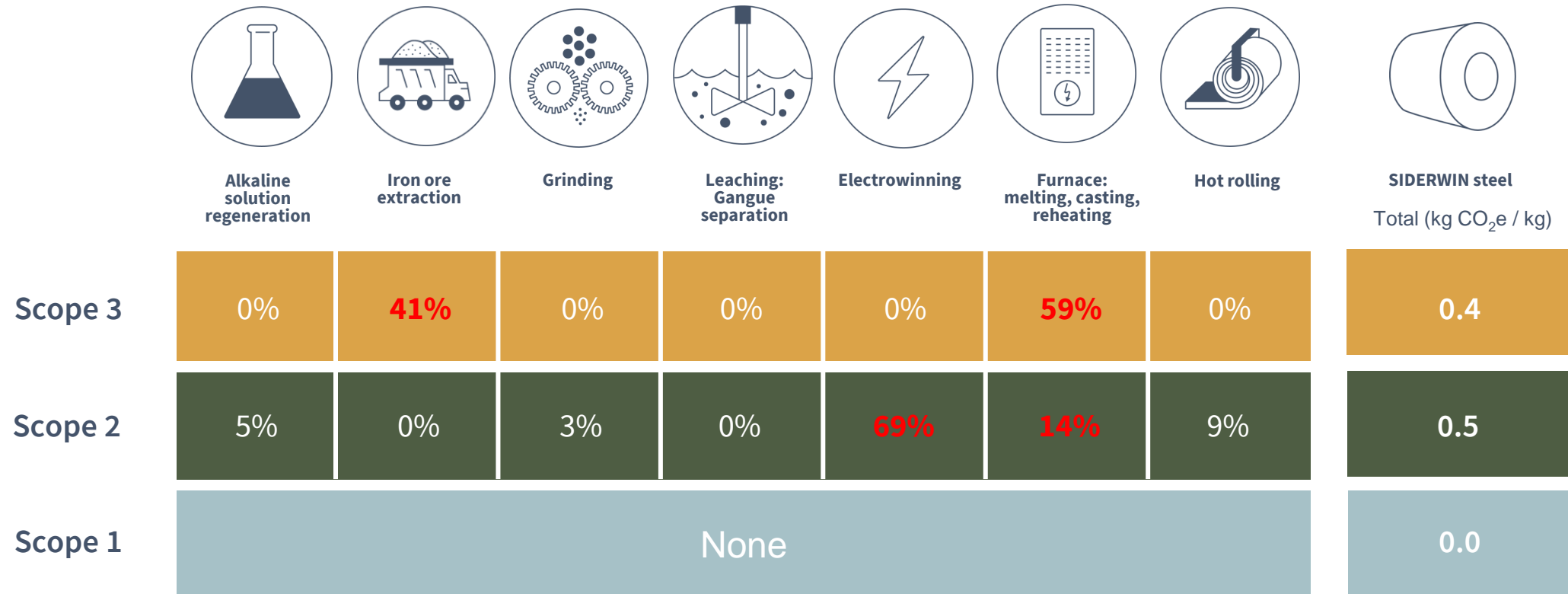
The **BF-BOF** technology serves as reference technology. It is modelled using a dataset from the ecoinvent database representing a best available technology (BAT).

- **Scope 1** emissions represent 60% and 73% of the overall footprint, depending on the steel grade.

The **SIDERWIN** technology allows to reduce the carbon footprint by **60-74%** compared to the BF-BOF technology depending on the electricity mix.

- As the processing route is optimised to be **fully electrified**, no scope 1 emissions occur.
- Scope 2 emissions come **from 4.2 MWh** electricity consumption.
- Scope 3 emissions represent 48% of the footprint in the scenario with the DSR, nuclear & offshore mix.

Carbon footprint deep dive per processing stage



Additional environmental indicators



Another material indicator for still is **human health**, given that global steel contributes about as much to air pollution as EU27 countries**.

SIDERWIN can reduce the impact on human health by around **25%** due to the **elimination of respiratory inorganics emitted during the coking process**.

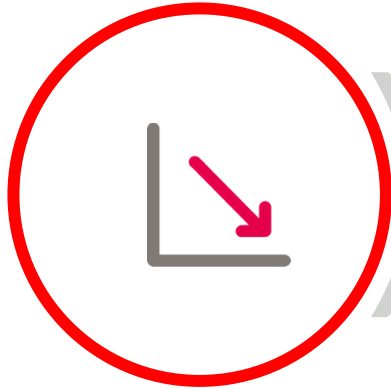
There are trade-offs for **water consumption and land use**, due to scope 2 electricity use for SIDERWIN, that involves indirectly:

- **water evaporated from hydropower reservoir** and from **cooling water used to produce nuclear electricity**
- **forest land occupation** to produce wood chips used for **bioenergy production**.

However, these indicators are considered as **less material** because steel production uses few agroforestry products which makes its influence on water consumption and land use secondary. The choice of **electricity mix can minimize these trade-offs**, e.g. by using more wind and photovoltaic electricity.

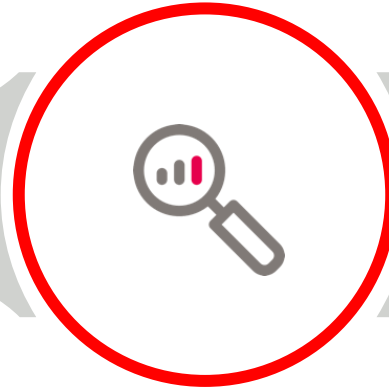
**CEIP (2021): Air pollution from Global Steel Industry – An International Benchmarking of Criteria Air Pollutants Intensities

The potential of SIDERWIN in terms of steel decarbonisation



UP TO 74% FOOTPRINT REDUCTION PER TON

Thanks to its innovations, the SIDERWIN technology could allow to reduce the footprint of steel by up to **74% per ton by 2050** and **eliminates direct emissions.**



REDUCED IMPACT ON HUMAN HEALTH

Further improvements of the route include a **reduction on human health impacts** as well as a reduced energy footprint.



AN ASSET FOR THE EU STEEL ROADMAP

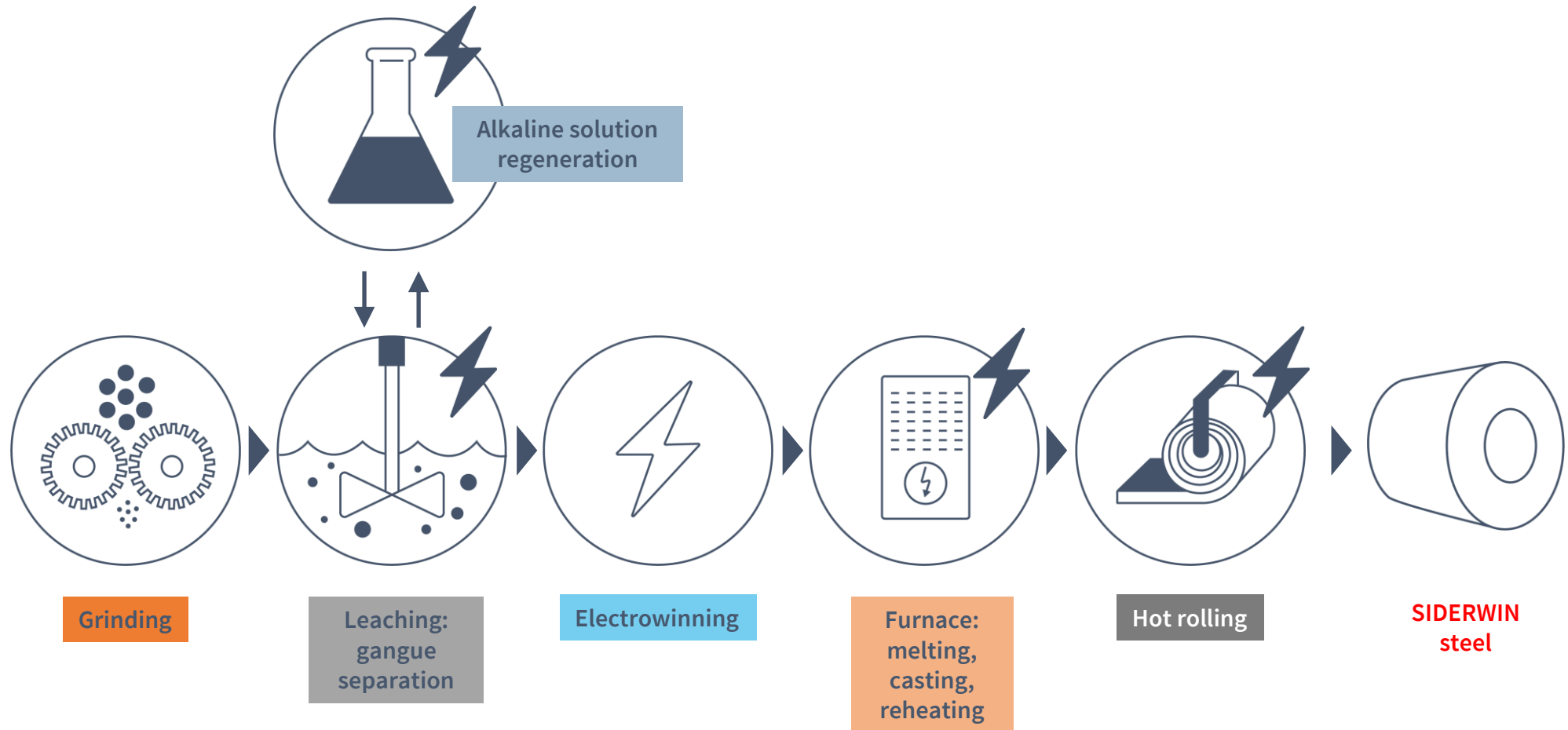
The SIDERWIN technology is thus a precious route for reducing the footprint of the steel sector and attaining its neutrality objective in 2050.

Costing / Economic viability of SIDERWIN

Modelling the SIDERWIN Technology

System boundaries: from raw materials extraction to factory gate.

The route is optimized to be fully electrified.



Modelling the SIDERWIN Technology



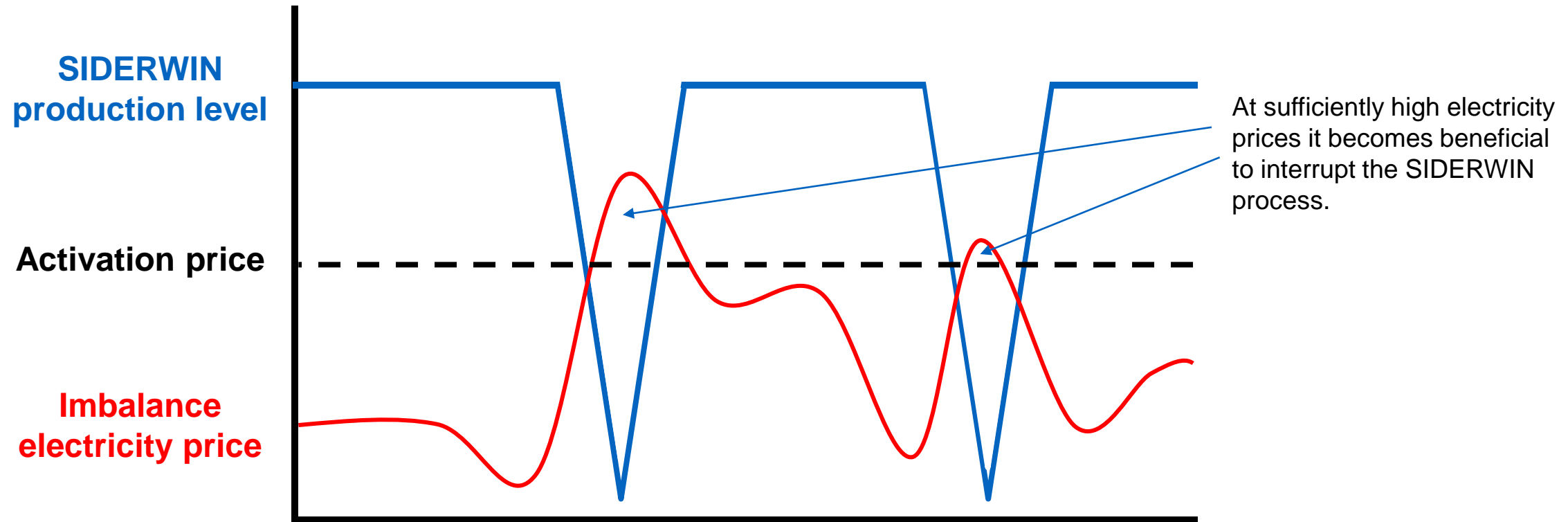
Costing / Economics

- Economics is based on an NPV analysis of cost data and revenue streams.
 - Cost data is based on CAPEX and OPEX data based on an Life Cycle Costing analysis of the individual process steps as per earlier slide, as well as costs of iron ore and energy in the form of electricity.
 - Revenue streams consist of sale of HRC product, flexibility income and possibly sales of Green Certificates.
 - All data is calibrated for a conceptual plant-size.
- Uncertainty is captured through the use of scenarios for the main parameters of influence.

Flexibility Income


- The SIDERWIN Technology as envisaged is a process with some flexibility built in.
- In general, steel production is a 24/7/365 process other than during periods of maintenance/planned outages.
- However, the SIDERWIN technology is – within limits -- a flexible process:
 - Around 5 % of the operating hours per year are available for ramp-down of the production.
- This flexibility can be offered to the electricity market to help Transmission System Operators maintain the integrity of the Grid:
 - High real-time electricity prices suggest a shortage of supply; temporarily reducing the offtake of electricity will create an income stream through the so-called imbalance market.
 - The electricity price activation level has to be high enough to offset loss of margin on the sale of steel.
 - Conservative analysis suggests a possible annual income stream of hundreds of millions €.

Flexibility of the SIDERWIN Technology



Conclusions

- Based on current technical and economic data the SIDERWIN Technology has the **potential to be profitable** at the time of commercialisation.
- The economics can be significantly improved through the **valorization of flexibility**.
- As the technology moves through the TRL levels the expectation is that the cost figures will improve through learning and thereby enhance the economics.
- An additional potential income stream would be the issuance of Carbon Credits. The value of these at the time of commercialisation of the SIDERWIN is difficult to assess.
- Because of the high dependency on sustainably produced electricity, the spatial location of future steel plants will be different from today (close to wind/solar parks instead of just near waterways). **The integration between such large electricity consumers and the electricity grid requires close attention.**

The background is a dark, artistic composition of technical drawings and mechanical parts. It includes various engineering sketches, cross-sections, and isometric views of mechanical components like bearings and gears. The drawings are overlaid on a dark, textured surface, possibly wood or a dark cloth, creating a professional and technical atmosphere.

Thank you
for your attention

Questions?



Development of new methodologies for Industrial
CO₂-free steel production by electro-winning

Conclusions and Perspectives

Valentine Weber-Zollinger – Coordinator ArcelorMittal
Webinar March 23rd 2023

The background of the slide is a blurred photograph of a modern office interior. Several people are visible as dark silhouettes against a bright, hazy light coming from large windows. The people appear to be in motion, creating a sense of a busy, dynamic work environment. The overall color palette is dark and moody, with the light from the windows providing a warm, yellowish glow.

Conclusions

ΣIDERWIN's main results & key messages

- Siderwin technology has been scaled up:
 - Cathode size up to 1.25 m² is feasible.
 - Gas management is key.
 - Electrolyte flow uniformity is required.
 - Electrolysis cell energy use confirmed at pilot scale.
- Siderwin technology can contribute to future carbon neutral steelmaking:
 - Almost no direct CO₂ emissions.
 - At least -60 % carbon footprint compared to traditional BF-BOF route.
 - Without compromising environmental footprint compared to BF-BOF route.

ΣIDERWIN's main results & key messages

- Σiderwin technology can contribute to the balance of the power system:
 - Fully electrified primary production.
 - The European power system can meet the additional ΣIDERWIN demand with carbon-free means.
 - Flexible process, low T (°C).
 - Demand Side Response can boost profitability.
 - Σiderwin technology can contribute to the deployment of RES.
- Σiderwin technology can contribute to circular economy:
 - Several potential alternatives studied: from steel industry, from aluminum industry, from nickel hydrometallurgical purification, from copper and ferronickel production.
 - Mill scales from steel industry was the most promising alternative material at this stage of technology development.
 - Other all alternatives were promising from lab-scale studies & more work must be done before scaling-up.

The background image is a blurred photograph of a modern office interior. Several people are visible as dark silhouettes against a bright, hazy light coming from large windows. The people appear to be in motion, with some standing in groups and others walking. The floor is highly reflective, creating clear mirror images of the people and the light from the windows. The overall color palette is dominated by dark blues, greys, and a warm, golden-yellow glow from the light source.

Perspectives

ΣIDERWIN is a promising innovative technology for the future of steel



Near zero direct CO₂ emissions.

Σiderwin technology is an electrowinning technology and does not use coal, coke or other intensive fuels. It is thus one of the lowest CO₂ emitting technologies.



High energy efficiency.

Σiderwin is based on a low temperature iron ore electrolysis. It is thus more energy efficient than other new generation low-carbon steel manufacturing technologies.



Cost competitive.

Thanks to its energy efficiency, Σiderwin is competitive to other low-carbon steel manufacturing technologies.



Strong scalability / Modular.

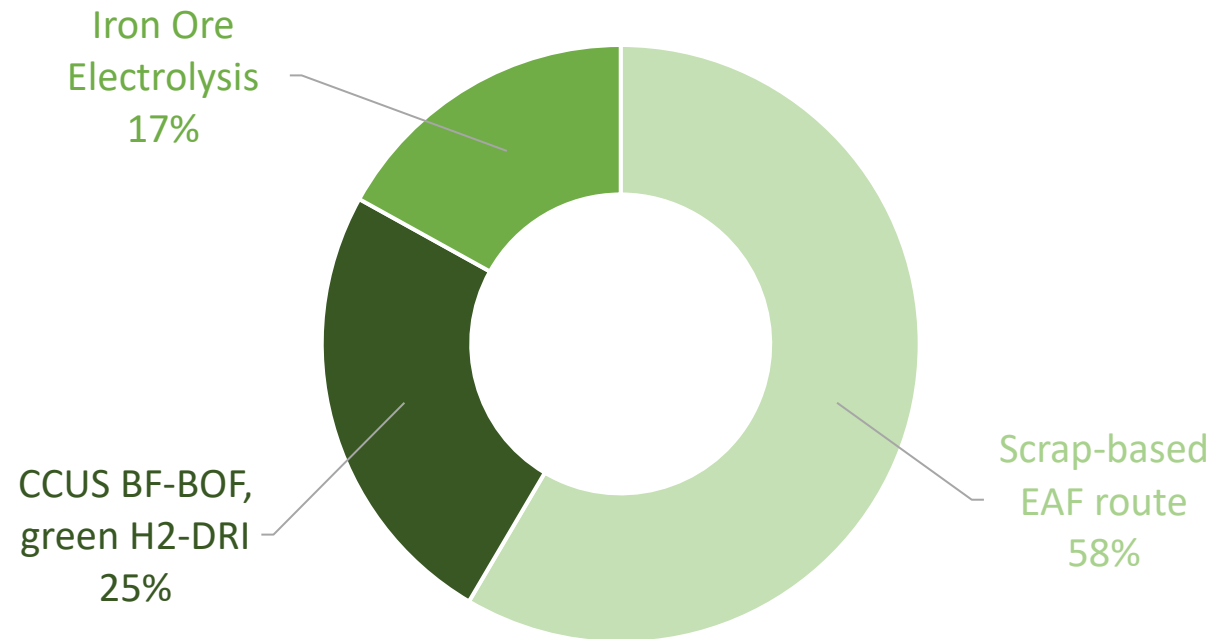
Electrowinning can easily adapt to any production capacity of plants, thanks to its modular design. Scale-up can thus be managed with limited complexity.



Streamlined operations.

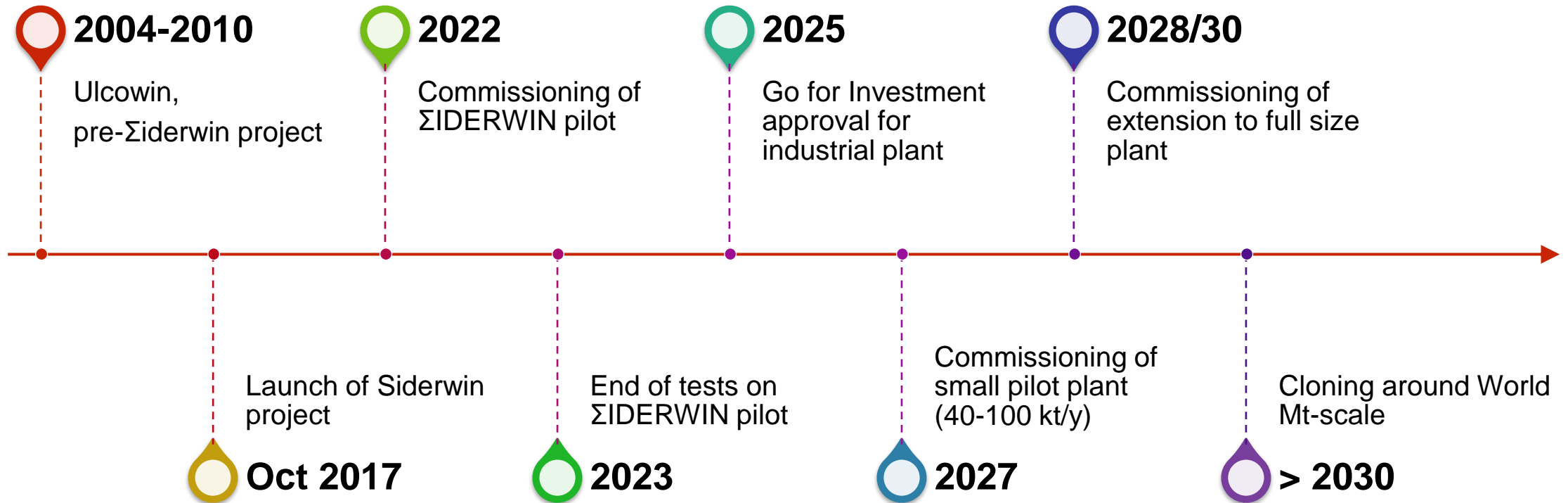
Unlike its green alternatives, Σiderwin does not require large infrastructure for H₂ distribution / storage or CO₂ capture. Beside its low temperature process is suitable for start and stop utilisation matching the specificities of renewable.


Worldwide low carbon steelmaking production in 2050



From AM internal study

Roadmap for the industrialization of the iron electrowinning



The background is a dark, artistic composition of technical drawings and mechanical components. It features several sheets of paper with detailed blueprints, including cross-sections of shafts, gears, and housing parts. Scattered across the papers are various mechanical parts: a ball bearing, a pulley, a small gear, and a custom-machined metal bracket. A wooden ruler and a pencil are also visible, suggesting a workshop or engineering office environment. The overall tone is professional and technical.

Thank you
for your attention
