ΣIDERWIN project
Electrification of primary steel production for direct CO$_2$ emission avoidance.
Outlook

1. Steel production and its environmental significance
   – Main figures
   – Steel – Energy coupling

2. New steel process for low CO$_2$ emissions
   – Primary steel production by electricity
   – Chemical route to solve multivalencies of iron

3. Electrolysis processing route
   – Design by thermodynamic optimisation
   – $\Sigma$IDERWIN project
Steel production and use

Yearly production (Mt)

1880 1900 1920 1940 1960 1980 2000 2020

Iron Ore

Crude Steel

WorldSteel
USGS

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Steel production and use

• Steel – Energy coupling

No steel without energy

EUROFER - The European Steel Association

~500 kg\(_{\text{Carbon}} \cdot \text{t}^{-1}\)\(_{\text{steel}}\)

~267-500 t\(_{\text{steel}} \cdot \text{MW}^{-1}\)

No energy without steel
Steel production and use

- \( \text{CO}_2 \) emissions

The steel industry generates between 7 and 9% of direct emissions from the global use of fossil fuel.

Energy

| Energy | 18.6 GJ.t\(^{-1}\)\text{steel} | 5.2 MWh.t\(^{-1}\)\text{steel} |

\( \text{Fe}_2\text{O}_3 + \text{C} + \text{O}_2 \rightarrow \text{CO}_2 + \text{Fe} \)
New steel process for low CO$_2$ emissions

- Primary steel production: energy need

\[
\frac{1}{2} \text{Fe}_2\text{O}_3 \text{ (s, 25ºC)} \rightleftharpoons \text{Fe} \text{ (s, 25ºC)} + \frac{3}{4} \text{O}_2 \text{ (g, 1 atm, 25ºC)}
\]

- Total energy need :
  \[\Delta H = 2.1 \text{ MWh.}t_{\text{Fe}}^{-1} \text{ or } 7.4 \text{ GJ.}t_{\text{Fe}}^{-1}\]
- Heat need 10% of total energy :
  \[\Delta H - \Delta G = 0.2 \text{ MWh.}t_{\text{Fe}}^{-1} \text{ or } 0.7 \text{ GJ.}t_{\text{Fe}}^{-1}\]
heating is taken by cooling atmosphere
- Work need 90% of total energy :
  \[\Delta G = 1.9 \text{ MWh.}t_{\text{Fe}}^{-1} \text{ or } 6.7 \text{ GJ.}t_{\text{Fe}}^{-1}\]
New steel process for low CO$_2$ emissions

- Choice of an energy form to produce iron metal

$$\frac{1}{2}\text{Fe}_2\text{O}_3 \ (s, \ 25^\circ C) \rightleftharpoons \text{Fe} \ (s, \ 25^\circ C) + \frac{3}{4}\text{O}_2 \ (g, \ 1\text{atm, } 25^\circ C)$$

**Electrical** $\Delta V = 1.28 \text{ V}$
- at $25^\circ C$
- $1\text{atm}$, $v=0$
- no reactant

**Mechanical**
- Vacuum $P_{\text{O}_2} = 10^{-87}$ atm
- Centrifugation $v=500 \text{ km.s}^{-1}$
- at $25^\circ C$
- $\Delta V=0$
- no reactant

**Chemical**
- $\mu=\text{CH}_2\text{O}$
- at $25^\circ C$
- $1\text{atm}$, $v=0$
- $\Delta V=0$

**Thermal**
- $T=3414^\circ C$
- at $1\text{atm}$, $v=0$
- no reactant
- $\Delta V=0$
New steel process for low CO$_2$ emissions

- Chemical energy form
  
  \[
  \frac{1}{2} \text{Fe}_2\text{O}_3 (s, 25^\circ\text{C}) + X \rightleftharpoons \text{Fe} (s, 25^\circ\text{C}) + \text{XO}_{3/2}
  \]

- No adjustment of chemical potential.
New steel process for low CO$_2$ emissions

• Electrical energy form:
  – it provides thermodynamic need.
  – It controls activation, kinetic.
  – It is adjustable.

► It requires electrical charges to transfer electrical energy into chemical energy by charge separation.
New steel process for low CO$_2$ emissions

**Acid:**
- Higher $\Delta$E
- Soluble cations
- Multiple cations

**Alkaline:**
- Slightly higher $\Delta$E
- Low solubility
- Single cation

Pourbaix diagram
New steel process for low CO$_2$ emissions

- Electrochemical mechanism of hematite reduction

1. Chemical reaction
2. Galvanic coupling
3. ElectrocrySTALLisation

Pourbaix diagram

\[
\begin{align*}
H\text{FeO}^- + Fe_2O_3 &\rightarrow Fe_3O_4 + OH^- \\
Fe_3O_4 + Fe + 4OH^- &\rightarrow 4H\text{FeO}^- \\
H\text{FeO}^- + H_2O + 2e^- &\rightarrow Fe + 3OH^- \\
\end{align*}
\]

<table>
<thead>
<tr>
<th>Minerals</th>
<th>Conductivity (S.cm$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe</td>
<td>$1 \times 10^7$</td>
</tr>
<tr>
<td>$\alpha$ Fe$_3$O$_3$</td>
<td>$10^{-9}$</td>
</tr>
<tr>
<td>Fe$_3$O$_4$</td>
<td>$2 \times 10^2$</td>
</tr>
</tbody>
</table>
New steel process for low CO$_2$ emissions

• Experimental check on a single particle
Electrolysis processing route

- Chemical route to solve multivalencies of iron

\[
\frac{1}{2} \text{Fe}_2\text{O}_3 \rightarrow \text{Fe} + \frac{3}{4}\text{O}_2
\]

- Low temperature electrolysis: 110°C.
- Conductive aqueous alkaline electrolyte medium 50wt% NaOH - H₂O.
- Electrolysis is applied to 10 µm hematite solid particles rather than dissolved ions.
- High reaction rate with current density 1000 A.m⁻².
- Anodic gaseous O₂ production.
- Non-consumable anode.
- Cathodic Iron grown as solid state deposit.
- Non critical elements in electrode materials, Ni anodes.
Electrolysis processing route

• Design by thermodynamic optimisation

- The condition of simultaneous uniform potential and current density is constant curvature electrodes.
- Separation of reaction products by proper orientation towards gravity. Ratchet effect by gravity separation of oxygen from iron.
- Uniform and non-accumulating supply of solid particles to the cathode surface by moderate electrolyte flow rate.
- Anode is a gas-electricity exchanger: maximum openness to gas upward flow, minimum inter electrodes gap distance.
- Full collection and minimum residence time of gas by a 45° electrodes inclination and counter flowing gas. Bubble engineering.

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Electrolysis processing route

- Steady operation: thermal, hydraulic, electric.
- No separator as membrane, diaphragm between electrodes.
- Distance between electrodes 1 cm.
- Productivity x3 compared to Ni et Co.
- Self-standing, stiff, compact and conveyable metal plates.
- Low voltage $\Delta V=1.7\text{V}$.
- Full recovery of oxygen gas.
- Cheap construction materials.
Electrolysis processing route

• SIDERWIN project
• 5 years project 2017-2022
• Budget: 6.8 M€ includes 2.2 M€ for pilot.
• 7 different countries.
• 12 partners: 4 Companies + 4 SMEs + 4 RTO
• Multisectorial: steel, non-ferrous and power.
• Coordinated by ArcelorMittal.
Electrolysis processing route

- **SIDERWIN project: objectives**
  - A new processing route for steel.
  - Overall energy consumption $3.6 \text{ MWh.t}^{-1}_{\text{Fe}}$ or $13 \text{ GJ.t}^{-1}_{\text{Fe}}$.
  - Reduction by 31% of the direct energy use.
  - Reduction by 87% of the direct CO$_2$ emissions.
Electrolysis processing route

Basic experimental work
- Corroborate basic observations
- Proof-of-concept
Components integration
- Configuration matches final application
- Full-scale prototype
- Engineering-scale prototype
- Operated final form
- Tested final form

2005
- Basic experimental work
2006
- Corroborate basic observations
2007
- Proof-of-concept
2009
- Components integration
2017
- Engineering-scale prototype
2022
- Operated final form

2005
- 10 µm iron oxide
- Iron metal

2006
- 10 µm iron oxide
- Iron metal

2007
- 10 µm iron oxide
- Iron metal

2009
- 10 µm iron oxide
- Iron metal

2017
- 10 µm iron oxide
- Iron metal

IERO
ASCoPE

SIDERWIN

SPRE

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Electrolysis processing route

- SIDERWIN project: development of key components of the technology to achieve TRL5

Electrodes: 3x1 m
Current intensity: 3kA
Power: 6kW
Electrolyte volume: 300L

Production:
Iron metal samples of 100kg.

Continuous and automated iron ore supply.
Gas oxygen collection.
Metal harvesting system.
Vertical extension for low footprint.
Electrolysis processing route

- **SIDERWIN project: operation in a relevant environment TRL6**

**Flexible metal production:**
- Contribute to integration of RES.
- Integration to power grid.

**Enlarge iron oxide sources:**
- Non-conventional feedstock.
- Residues from Al, Ni and Zn metallurgies.

**Develop new business models:**
- New service as residue treatment.
- New service as Demand Side Response.
Electrolysis processing route

- [https://www.siderwin-spire.eu/content/home](https://www.siderwin-spire.eu/content/home)
- [https://www.youtube.com/watch?v=0SG421hiKXA](https://www.youtube.com/watch?v=0SG421hiKXA)
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