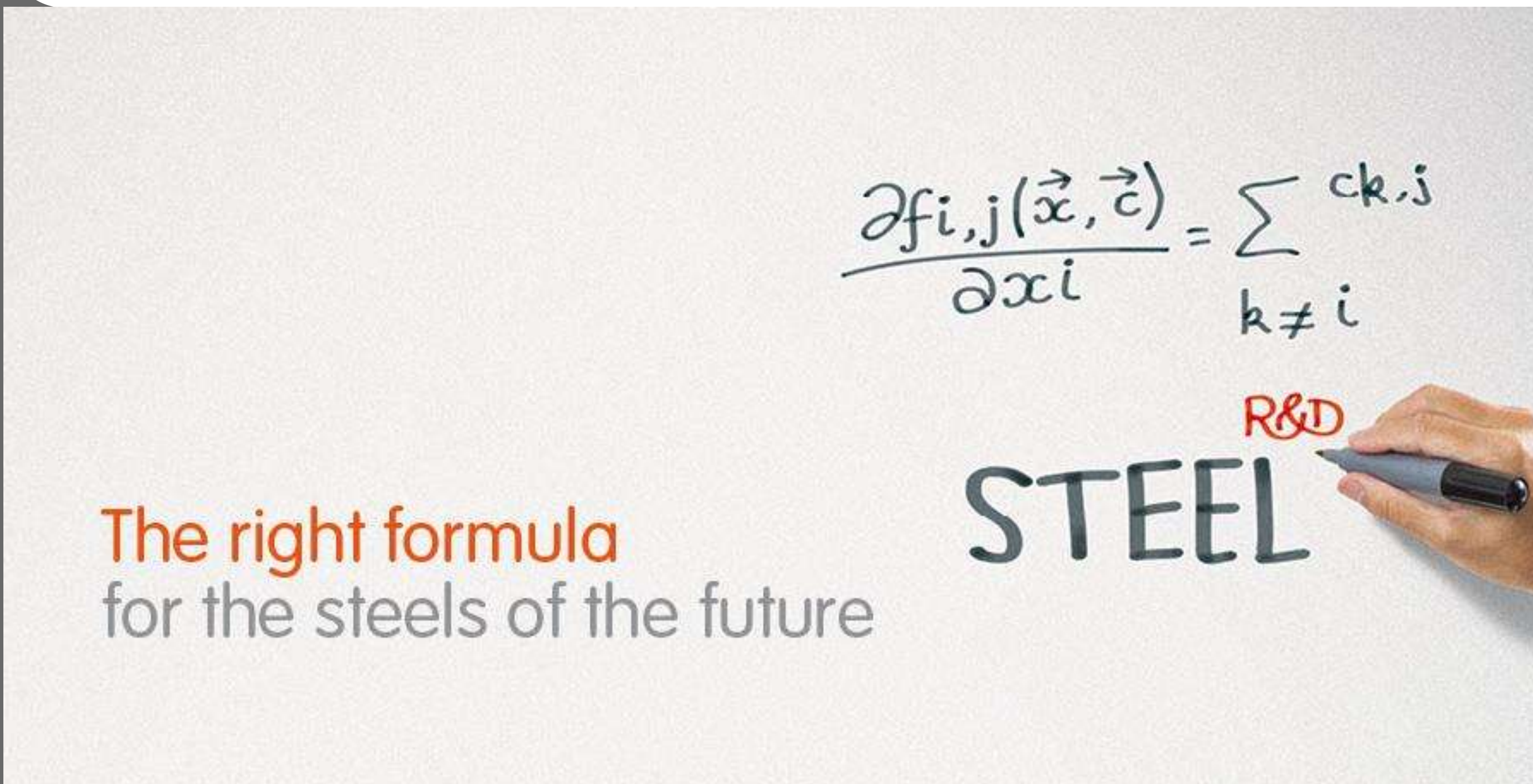
Global Research and Development

Massive production of primary iron metal by electrolysis

PRAXISforum "Electrolysis in Industry"



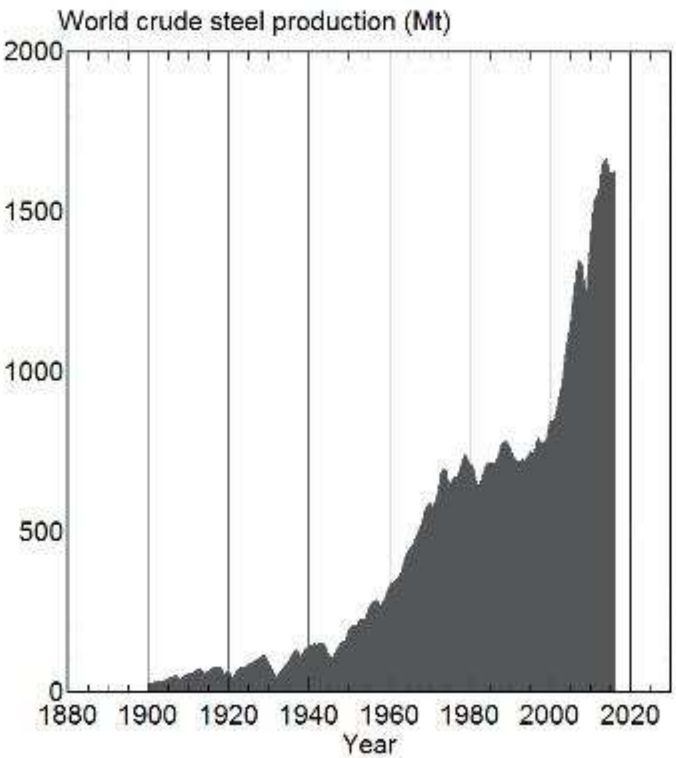
Outlook

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
   - SIDERWIN project

Steel production

Steel production

- World steel production (2016)



https://www.worldsteel.org

– 1 628 Mt crude steel.

– 75% primary steel.

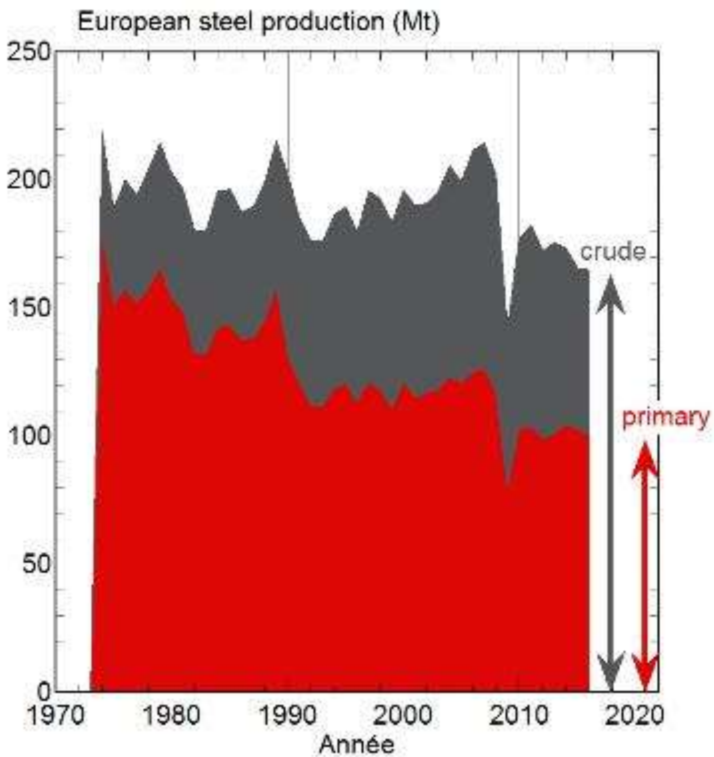
– 1000 G$ turnover.

– BAU scenarios predict 2.0 à 2.5 Gt in 2050.

– Accounts for 6.7% GHG emissions.

Steel production

- European steel production (2016)

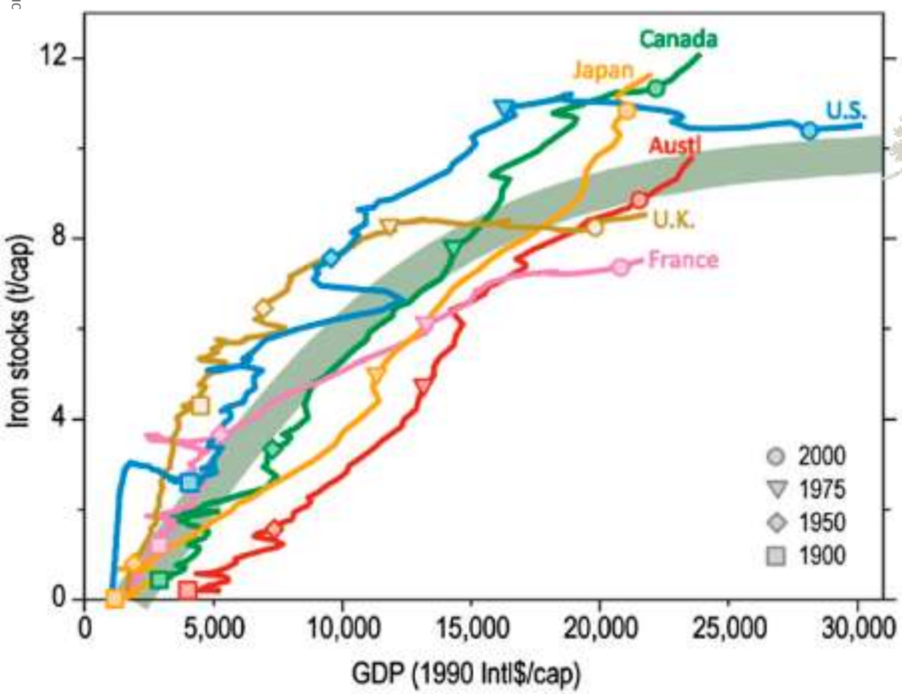


https://www.worldsteel.org

- 162 Mt crude steel (2016).
- 60% primary steel.
- 320 000 employees.
- 170 G$ turnover.
- 1.4% GDP.
- Second world largest productor.
- 236 Mt expected in 2050.
- Accounts for 5.3% GHG emissions.

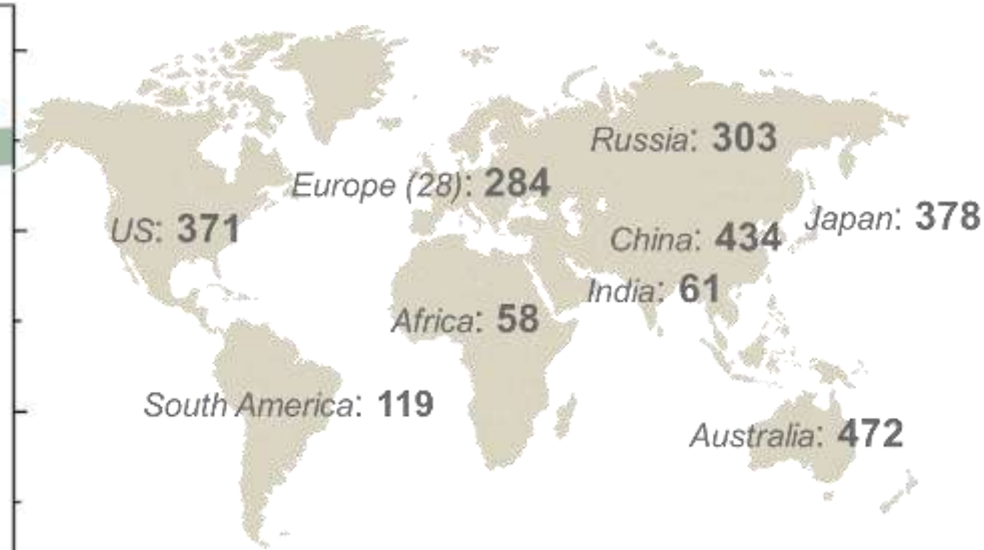
Steel production

Steel stock per capita



D. Müller et al. Patterns of Iron Use in Societal Evolution

Steel consumption per capita



https://www.worldsteel.org

- 20 Gt of steel in use worldwide

Steel production

- Steel production process: Blast Furnace Route

$$Fe_2O_3 + C + O_2 \rightarrow CO_2 + Fe$$

Fe_2O_3	C	CO_2	Fe
1.3t	0.5t	1.83t	1.0t


coke


Iron ore


Hot Rolled Coil

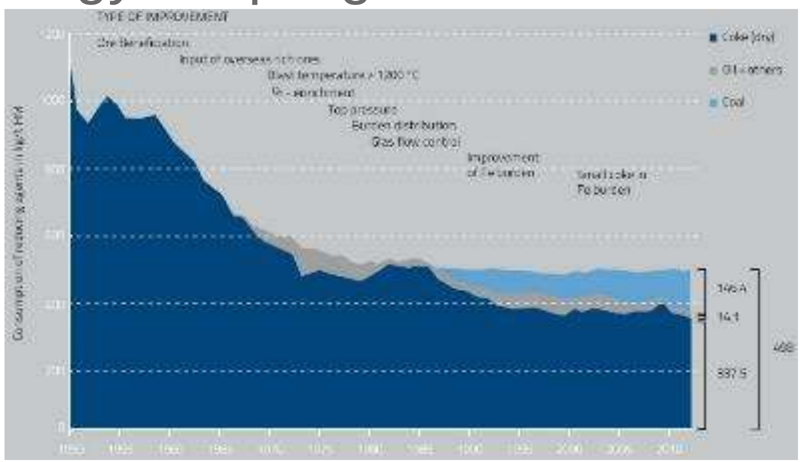
Steel production

- Steel – Energy coupling:

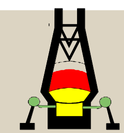
No steel without energy

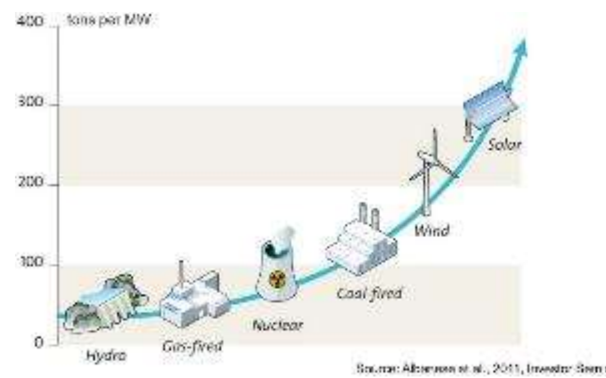
–

No energy without steel



EUROFER - The European Steel Association

	
	Blast Furnace
Energy	18.6 $GJ.t^{-1}_{steel}$
	5.2 $MWh.t^{-1}_{steel}$
CO_2	1.83 $t.t^{-1}_{steel}$

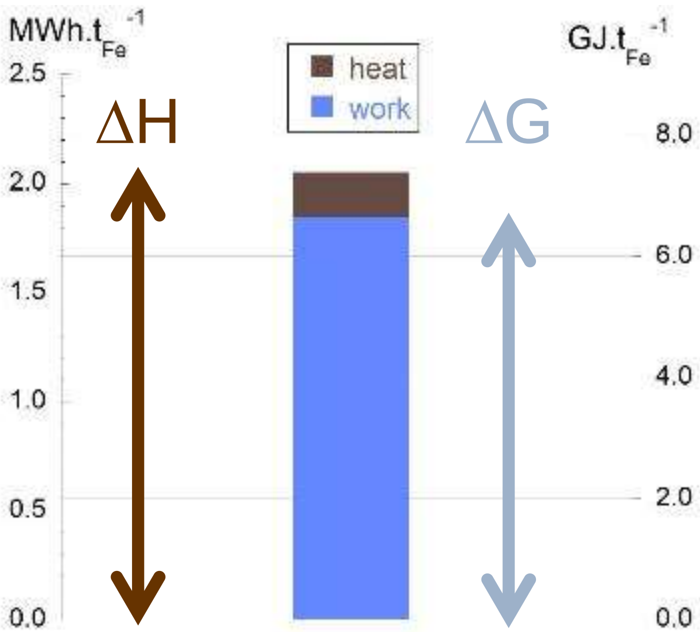


New steel process for low CO_2 emissions

New steel process for low CO_2 emissions

- Primary steel production: energy need.

$$\tfrac{1}{2}Fe_2O_3\ _{(s,\ 25^oC)} \leftrightarrows Fe\ _{(s,\ 25^oC)} + \tfrac{3}{4}O_2\ _{(g,\ 1atm,\ 25^oC)}$$



- Total energy need :

$\Delta H = 2.1\ MWh.t_{Fe}^{-1}$ or $7.4\ GJ.t_{Fe}^{-1}$

- Heat need 10% of total energy :

$\Delta H\text{-}\Delta G = 0.2\ MWh.t_{Fe}^{-1}$ or $0.7\ GJ.t_{Fe}^{-1}$

heat is taken by cooling atmosphere

- Work need 90% of total energy :

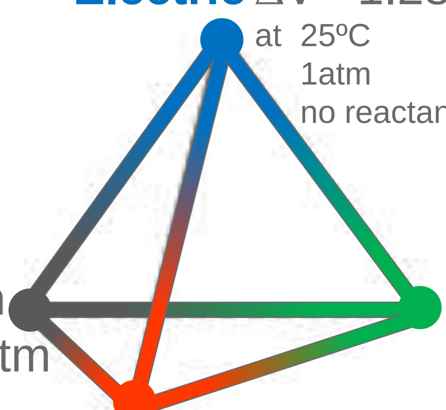
$\Delta G = 1.9\ MWh.t_{Fe}^{-1}$ or $6.7\ GJ.t_{Fe}^{-1}$

what source for work?

New steel process for low CO_2 emissions

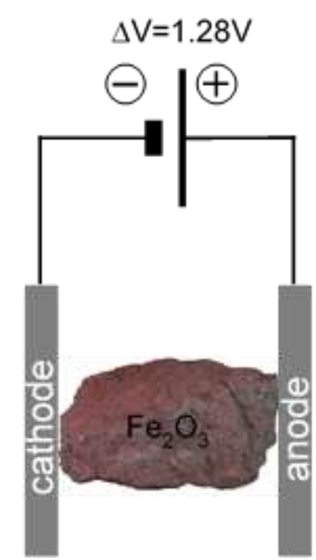
- Primary steel production: choice of an energy form.

$$\tfrac{1}{2}Fe_2O_3\ _{(s,\ 25^oC)} \leftrightarrows Fe\ _{(s,\ 25^oC)} + \tfrac{3}{4}O_2\ _{(g,\ 1atm,\ 25^oC)}$$



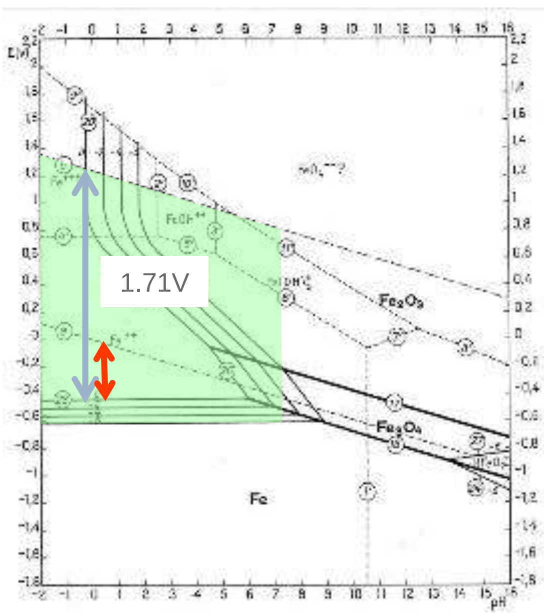
– Electrical seems particularly appropriate.

Which medium to separate ions?



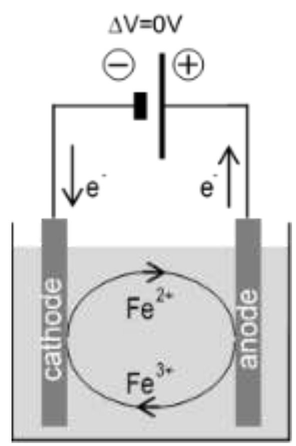
New steel process for low CO_2 emissions

- Acid chemical route: problem of iron multivalent ions



Pourbaix diagram

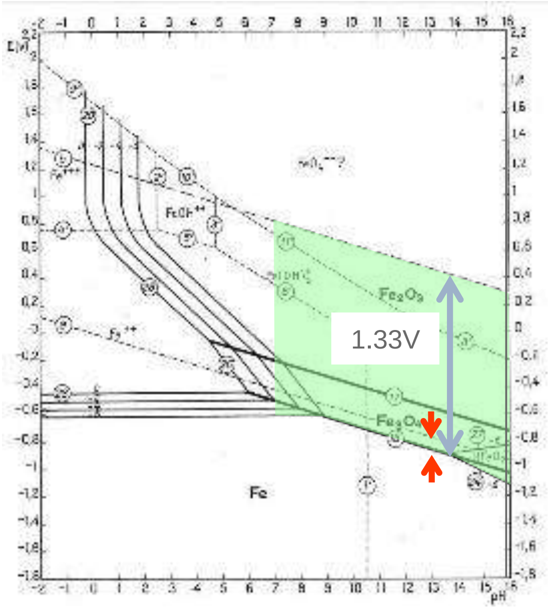
- Decomposition voltage is higher than thermodynamic minimum due to cation solvatation.
- Both Fe(II) and Fe(III) are soluble.



Chemical looping prevent iron metal production.

New steel process for low CO_2 emissions

- Alkaline chemical route solve multivalencies of iron.



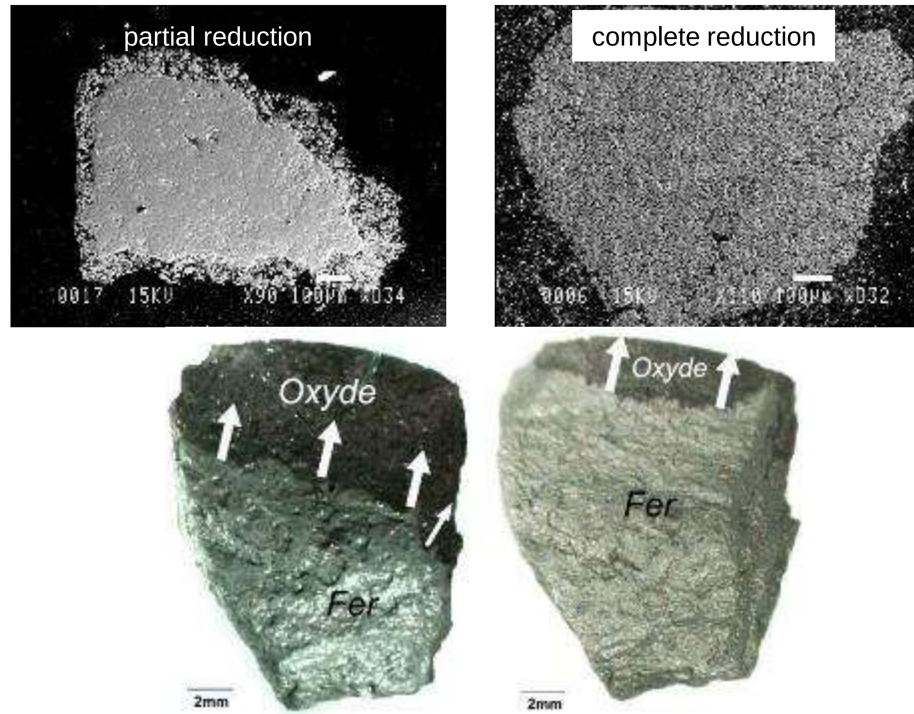
Pourbaix diagram

  - Decomposition voltage corresponds to magnetite.
  - Fe(III) is insoluble.
  - Fe(II) soluble in reductive conditions.
  - Magnetite is electronically conductive.

Is electrolysis at low solubility possible?

New steel process for low CO_2 emissions

- Alkaline chemical route solve multivalencies of iron



- Solid particles of hematite are electrochemically reduced

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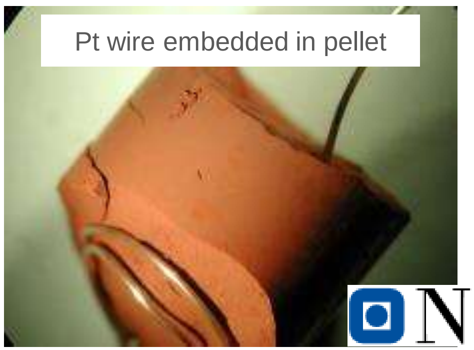
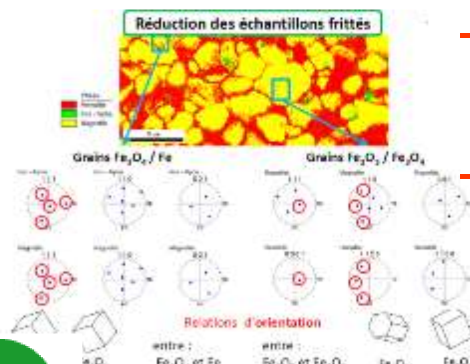
New steel process for low CO_2 emissions

- Alkaline chemical route solve multivalencies of iron



NTNU



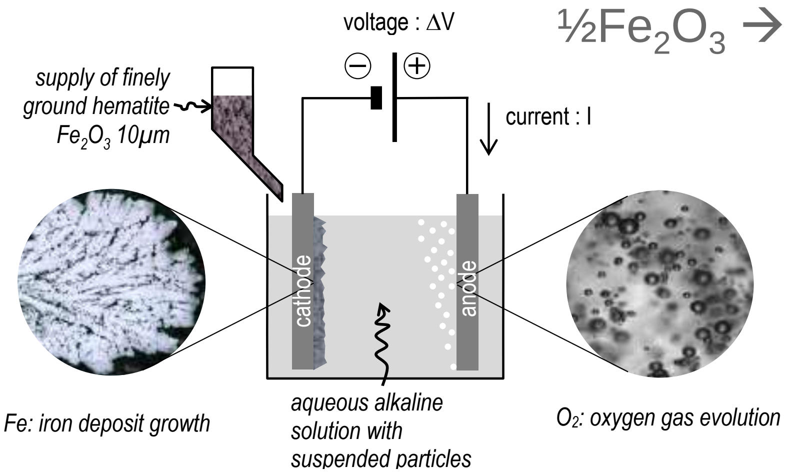
Chimie Paris ParisTech

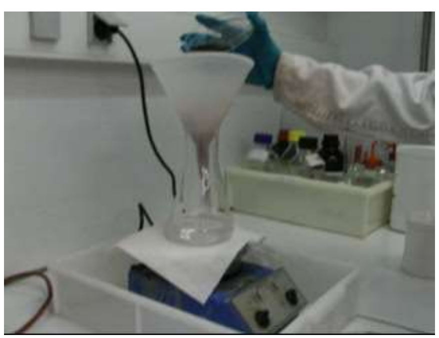
- Reaction progresses inward the particle.
- Magnetite is produced as an intermediate compound on hematite.
- Iron metal is produced as a separated solid phase.
- There is conservation of crystallographic orientations between the three phases.

New steel process for low CO_2 emissions

- Chemical route to solve multivalencies of iron

$$\frac{1}{2}Fe_2O_3 \rightarrow Fe + \frac{3}{4}O_2$$





- Low temperature electrolysis: 110°C.
- Conductive aqueous alkaline electrolyte medium 50wt% NaOH - H_2O.
- 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 O_2 production.
- Non-consumable anode.
- Cathodic Iron grown as solid state deposit.
- Non critical elements in electrode materials, Ni anodes.

Electrolysis processing route

Electrolysis processing route

- Design by “thermodynamic optimization”:
  1. Supply energy accurately in terms of amount, of form and intensity.
  2. Operation close to thermodynamic reversibility with a ratchet effect to give an orientation to progress.
  3. Operation as close as possible to surrounding conditions, minimise heat and pressure losses.
  4. Straight, once through flow, energy change of form, no loop, no internal recirculation, not stable intermediates.
  5. No chemical mixing, dissolution, dispersion.
  6. Minimised transfer resistances, low ohmic and viscous “frictions”.
  7. Uniformity in space of intensity parameters: no hot spots, not dead zones.
  8. Uniformity in time of intensity parameters : steady state, no transient.

Electrolysis processing route

- Design by thermodynamic optimisation

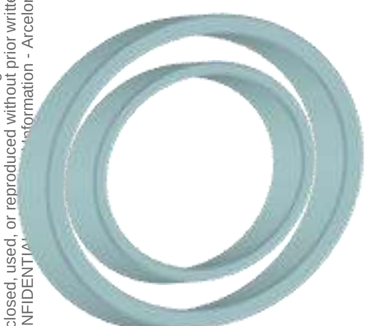
The condition of simultaneous uniform potential and current density is constant curvature electrodes.

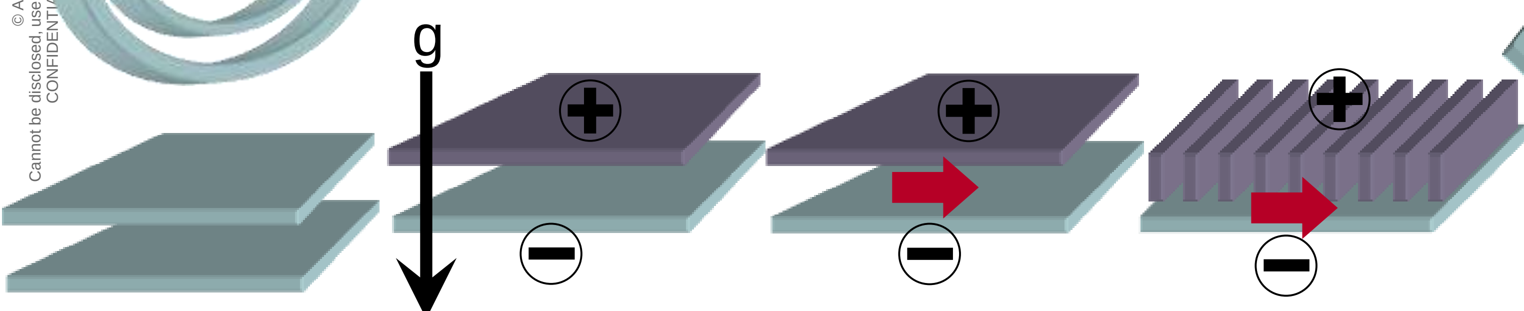
Separation of reaction products by proper orientation towards gravity. Ratchet effect by gravity separation of oxygen from iron.

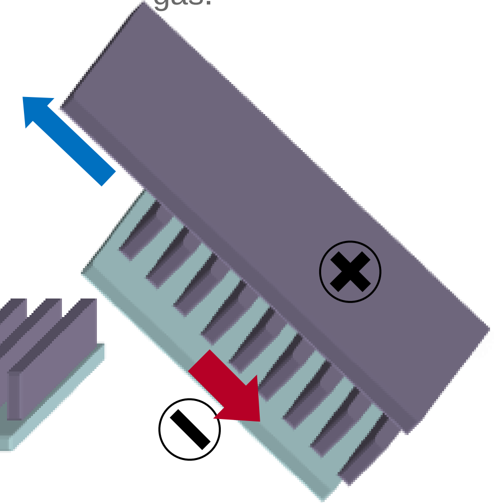
Uniform and non accumulating supply of solid particles to the cathode surface by moderate electrolyte flow rate.

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.







Electrolysis processing route

- Technological development of iron metal production by electrolysis:

  - Steady operation: thermal, hydraulic, electric.
  - No separator as membrane, diaphragm between electrodes.
  - Distance between electrodes 1cm.
  - Productivity x3 compared to Ni et Co.
  - Self-standing, stiff, compact and conveyable metal plates.
  - Low voltage $\Delta V=1.6V$.
  - 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: addressing primary steel production in the its simplest chemical route.
  - Direct decomposition of oxides.
  - Production of iron metal.
  - Energy supplied as electricity.
  - Treatment of naturally occurring oxides.
  - Breakthrough compared to conventional routes.

$$\tfrac{1}{2}Fe_2O_3 \rightarrow Fe + \tfrac{3}{4}O_2$$

$2\ Gt.a^{-1}$

$1.2\ Gt.a^{-1}$

Electrolysis processing route

- SIDERWIN project: objectives

1. A new processing route for steel.
2. Overall energy consumption 3.6 $MWh.t^{-1}_{Fe}$ or 13 $GJ.t^{-1}_{Fe}$.
3. Reduction by 31% of the direct energy use.
4. Reduction by 87% of the direct CO_2 emissions.

SIDERWIN project

TRL	
9	Operated final form
8	Tested final form
7	Full-scale prototype
6	Engineering-scale prototype
5	Configuration matches final application
4	Components integration
3	Proof-of-concept
2	Corroborate basic observations
1	Basic experimental work

Siderwin

ArcelorMittal

2017-2022 6.8M€

HORIZON 2020

LE PORTAIL FRANÇAIS DU PROGRAMME EUROPÉEN POUR LA RECHERCHE ET L'INNOVATION

SPIRE

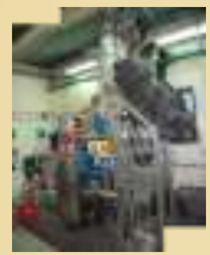
2017

2009

2007

2006

2005



VALORCO

IERO

ASCoPE

ulcos

ADEME

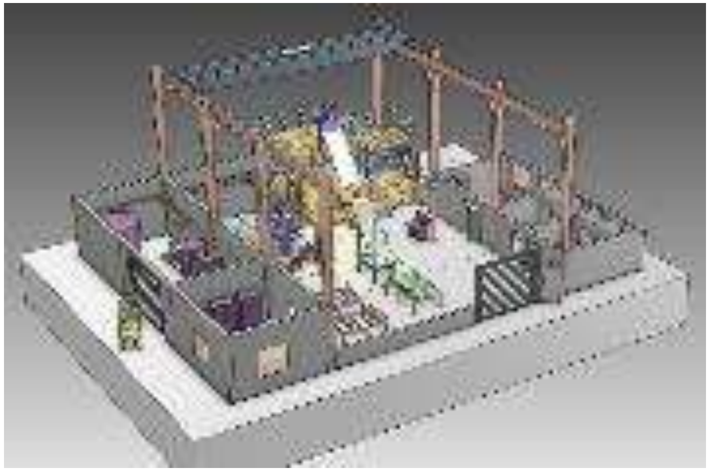
Research Fund for Coal & Steel

ANR

SIXTH FRAMEWORK PROGRAMME

Electrolysis processing route

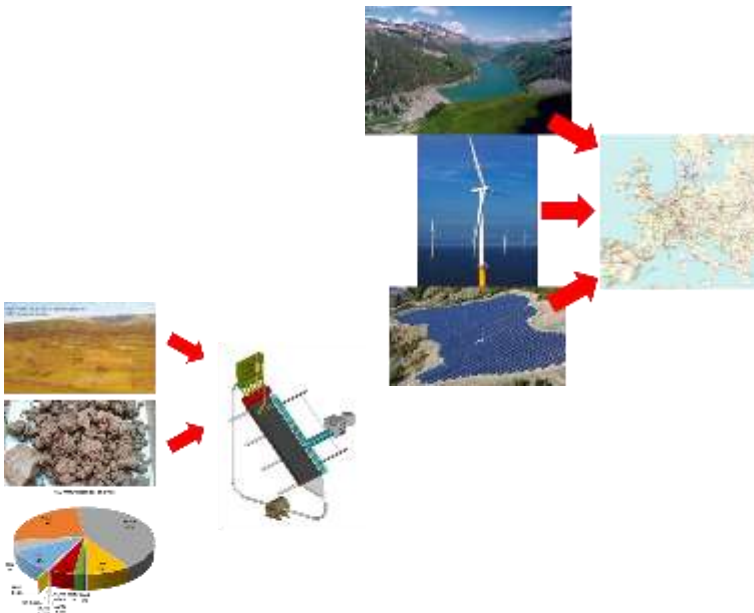
- SIDERWIN project: development of key components to achieve TRL5

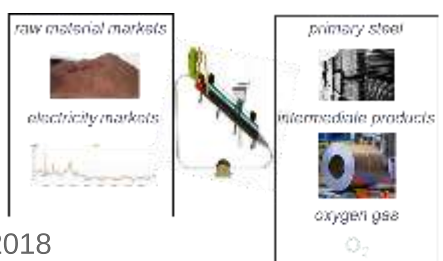


  - Continuous and automated iron ore supply.
  - Gas oxygen collection.
  - Metal harvesting system.
  - Vertical extension for low footprint.

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.

SIDERWIN project

https://www.siderwin-spire.eu/content/home

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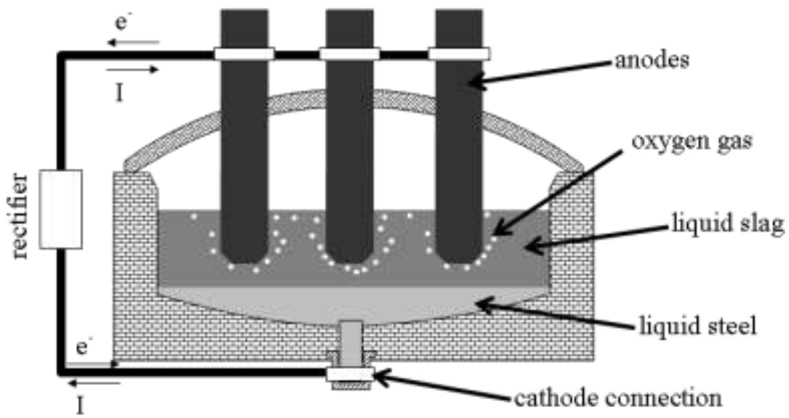
High temperature electrolysis

iron ore



molten steel