Pathways to Green Steel Production

Green Steel World, Essen, 4-5 April, 2023

Joachim von Schéele

Making our world more productive

Linde – Gases and Technologies Supporting Green Production of Steel

World's Largest Industrial Gases Company

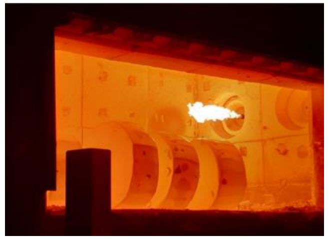
- Sales at $33 billion
- Market Capitalization at $170 billion
- Activities in 100+ Countries
- 65,000 Employees
- 6,600+ Patents
- Investing >$1 billion per year in Clean Energy
- Both Gases and Engineering (EPC)

World-leading Supplier of Hydrogen

- Sales $3 billion/year
- Active Across the Whole Value-chain
- Part-owner of ITM Power Electrolysis
- Building world's largest PEM Electrolyzers
- Cooperation with Ceres, BASF
- Tripling its Clean Hydrogen Capacity by 2028

Provider of Leading Technologies

- AOD 75% of world stainless steel production
- CoJet® 170+ installations in Electric Arc Furnaces
- REBOX® 180+ installations in Reheating & Annealing
- OXYGON® 200+ installations in Ladle Preheating



Linde Clean Energy Strategy

Linde as Integrator Across the Entire Hydrogen Value Chain

Grey H_2 | Blue H_2 | Green H_2 | H_2 Distribution, Conditioning & Application

	H_2 Inputs	H_2 Production	H_2 Distribution	H_2 Conditioning
H_2 value chain	Natural Gas	SMR, ATR… / …with CCS	Liquefaction; Trailers	H_2 refueling stations
	Renewable Power, Water	Electrolysis	Pipelines; Underground storage	Equipment & Tech Offerings
Linde's Clean H_2 Role	Partner	**Leader in all production** technologies	**Leader in all distribution** (technology & scale) incl. H_2 cavern	**Leader in H_2 fueling**

Linde H2 Assets

50+ years of experience

World-class technology

150+ SMR / PSA

80+ Electrolyzers

1,000km+ pipeline

1,600+ trailers

200+ refueling stations

$3 billion in H2 sales

Linde is a leader across the hydrogen value chain, agnostic to the hydrogen "colour"

Solutions Supporting Decarbonization of Steelmaking in the Near- to Mid-Term

- Hydrogen as Reductant and Fuel
- Production and Use of Low-Carbon Fuels
- Carbon Capture Storage & Utilization
- Energy-Efficiency Solutions Using Oxyfuel

Development of Use of Shaft-based Direct Reduction Processes

Picture from Voxna Bruk, pilot scale (1920)

The Swedish Professor Martin Wiberg (1894-1975) was the father of shaft-based Direct Reduction processes, later to be developed into well-known processes such as MIDREX (1969), HyL (1957/1980), etc.

Full scale operations in Sweden

Söderfors (1933-1961); 10 kt/y
Sandviken (1952-1980); 20 kt/y
Hällefors (1953-1963); 20 kt/y
Persberg (1953-1973); 40 kt/y
Hofors (1955-1978); 30 kt/y

Today the World Production is more than 90 Mt/y, about 80% using MIDREX technology.

55 Mt/y is produced in the MENA region.

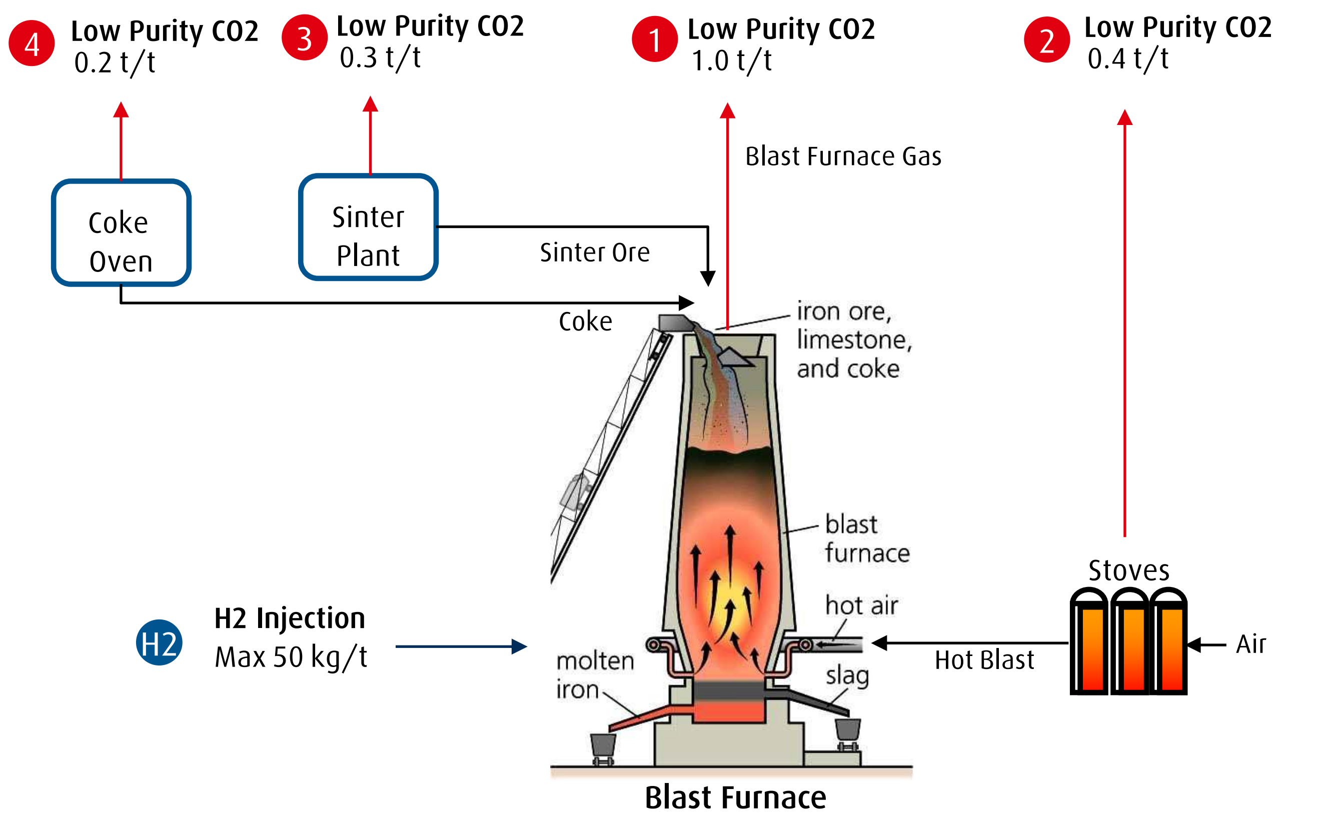
EU currently produces 0.5 Mt/y.

Carbon Capture and Use of Hydrogen are Primary Solutions to Decarbonize Iron Production

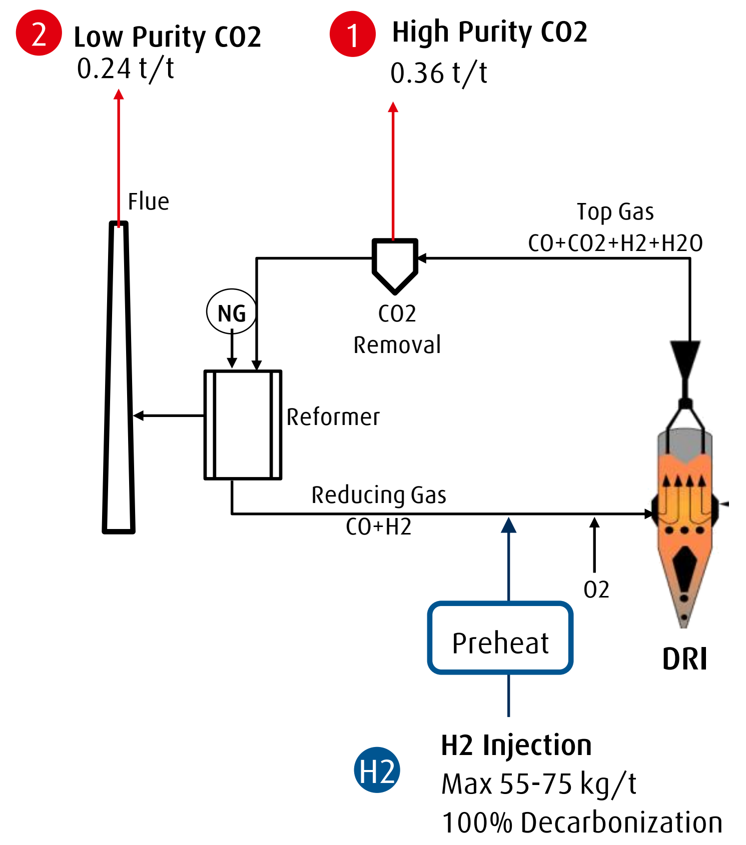
CCS

H2

Blast Furnace



DRI Plant

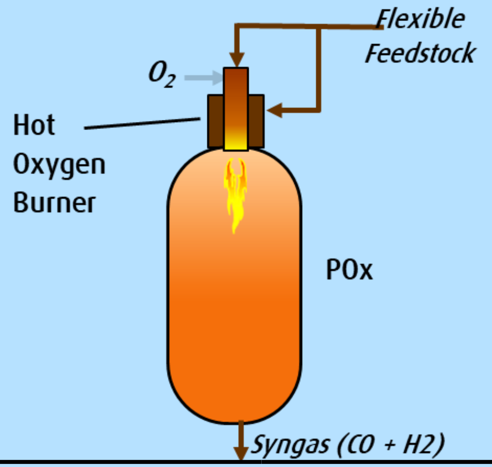


Gasification to Produce Low Carbon Fuels

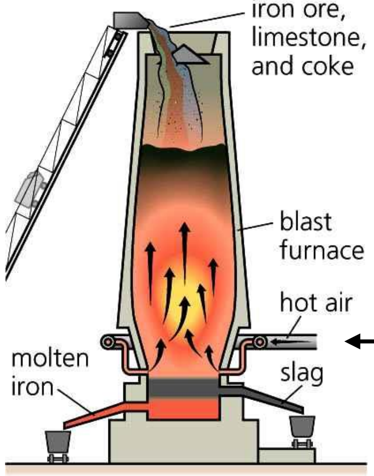
Example: Hot Oxygen Technology

Linde's Hot Oxygen Technology

External Gasification of low carbon feedstocks



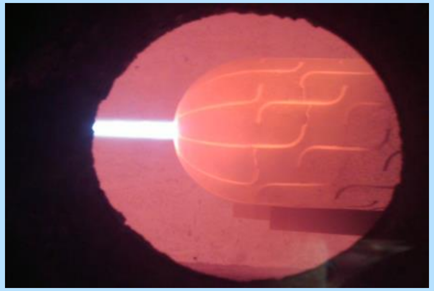
- Plastics
- Municipal Solid Waste
- Biomass/Pyoil
- Coke oven gas

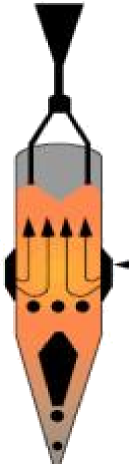


Blast Furnace

- Maximize injectant levels, coke replacement
- Achieve CO2 savings without cost penalty
- Maximize BF decarbonization, asset utilization

- Efficient, small-scale gasifier to generate *hot* syngas
- Up to 35,000 Nm³/h syngas per unit





DRI

- Alternate approach to decarbonization of DRI
- Advantages over H2:
  - Cost/economics
  - Source of carbon for DRI

Low Carbon Fuels

Example: Hot Oxygen Technology

Thermal Reactor System for coke oven gas

Demo Plant at Midrex Technology Center, Charlotte

Targets for parameters met/exceeded

- Syngas generated is ideal for the DRI Process

Sierra Biofuels, Nevada

- Gasification of Municipal Solid Waste (MSW) to clean syngas
- 175,000 TPY MSW → 50,000 m3/y syncrude
- Gasifier hot commissioning in progress, full plant commissioning in preparation
- Production of Sustainable Aviation Fuel (SAF)

Hydrogen Combustion Economics
Oxyfuel is a Prerequisite for Hydrogen Combustion

Hydrogen will be an expensive fuel

- Lowest anticipated cost of H_2 = €2/kg
- Equivalent to ~€15/GJ ($15/MM BTU)

Oxyfuel Combustion will be economically necessary with H_2 fuel

Air-fuel ⇨ **Oxyfuel** ⇨ **Oxyfuel w/ H_2**

Air-fuel	Oxyfuel	Oxyfuel w/ H_2
	20-60% CO_2 Savings	Full Decarbonisation

<u>Furnace atmosphere</u>

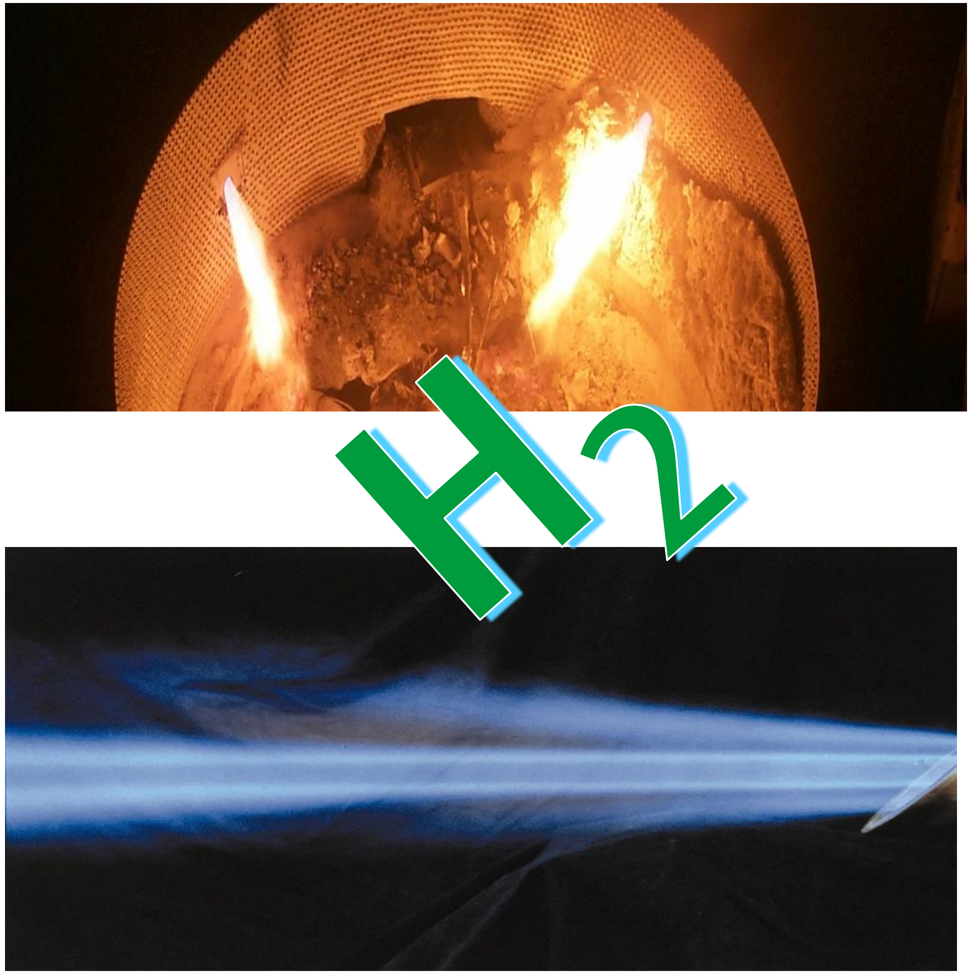
Air-fuel	Oxyfuel	Oxyfuel w/ H_2
~15% $H_2O(g)$	~55% $H_2O(g)$	~95% $H_2O(g)$

CoJet® Coherent Jet Technology – 170+ Installations

Revolutionized Electric Arc Furnace Steelmaking since 1996

Typical Cost Benefits Experienced

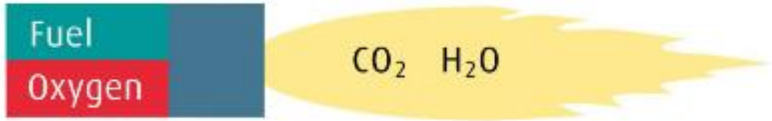
- **Reduced power consumption (5-20%)**
- **Increased productivity (3-50%)**
- **Improved yield (0.5-1.5%)**
- Elimination of supersonic lances and manipulators
- Significantly reduced maintenance
- Reduced refractory wear (5-10%)
- Reduced gunning
- Reduced electrode consumption (5-20%)
- Reduced injected carbon
- Improved delta life



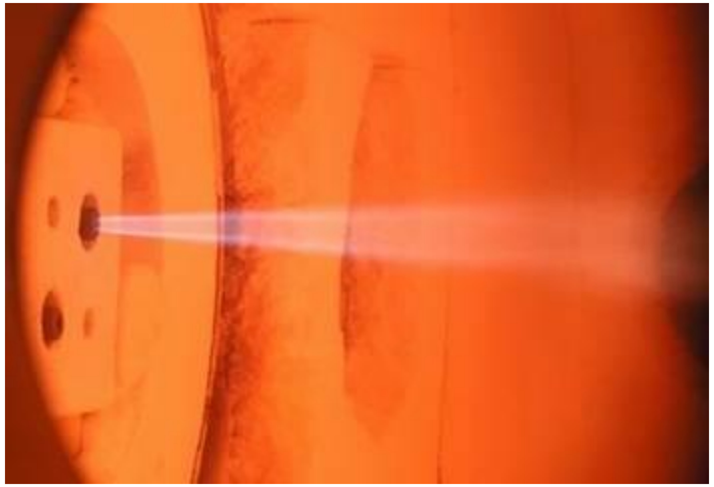
It has been demonstrated that Hydrogen is the best fuel for CoJet, producing the longest jets!

Conventional Oxyfuel and Flameless Oxyfuel

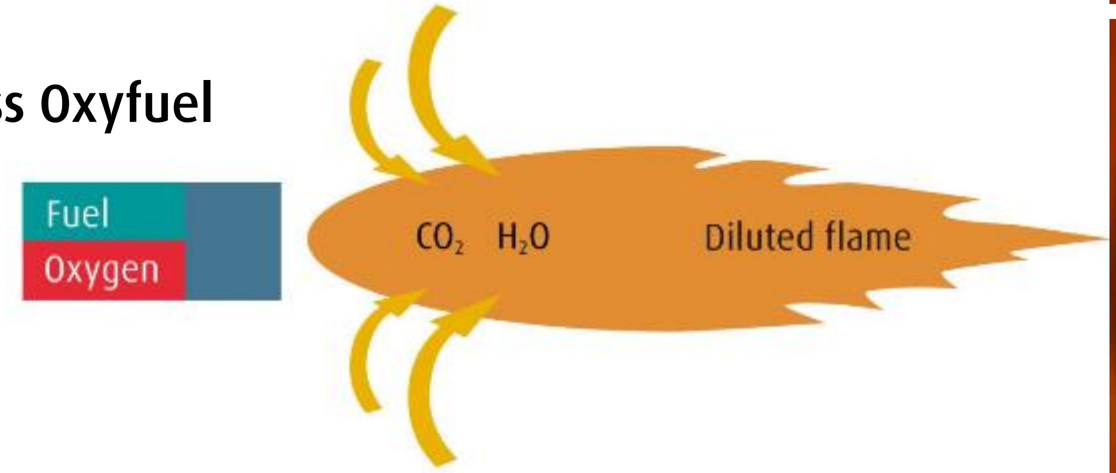
Conventional Oxyfuel



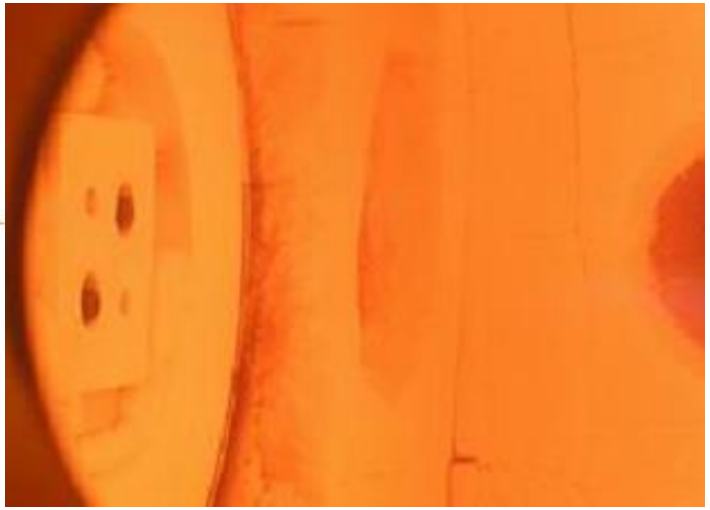
$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$ + HEAT



Flameless Oxyfuel

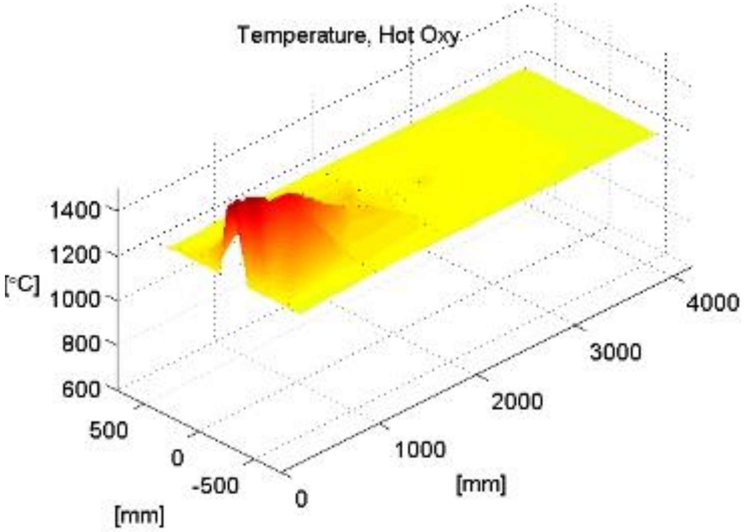


$CH_4 + 2O_2$ + Hot furnace gases $\rightarrow CO_2 + 2H_2O$ + HEAT

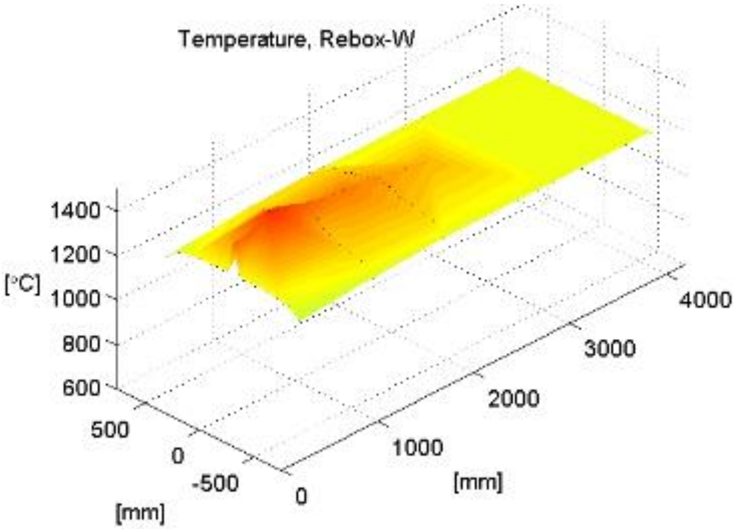


Flame Temperature Profiles of Conventional Oxyfuel and Flameless Oxyfuel

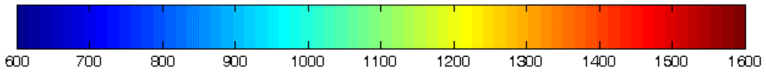
Data from evaluation by Royal Institute of Technology (KTH), Sweden; furnace at 1200ºC

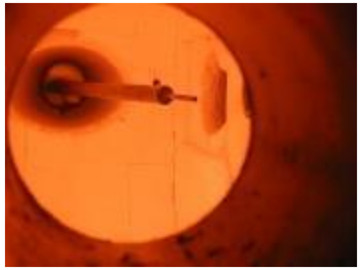


Conventional Oxyfuel



Flameless Oxyfuel





Same Peak Temp as Air-fuel, but Better Uniformity

No generation of Thermal NOx

Burner	Peak flame temp
Flameless Oxyfuel	1434˚C
Regenerative air-fuel	1398˚C
Conventional air-fuel	1404˚C

REBOX® Oxyfuel Solutions in Steel Reheating and Annealing
180+ Installations at 40+ Steel Mills

Installations of REBOX Oxyfuel Solutions in Steel Reheating have Resulted in:

- Capacity Increase by up to 50%
- Fuel Savings of up to 50% (some cases 65%)
- Reduction of CO_2 Emission by up to 50%, by 100% with H_2
- Reduction of NO_X Emission
- Improved temperature uniformity, <5°C
- Decrease of Scaling Losses by up to 50%

REBOX® Flameless Oxyfuel In Operation since 2003

The first installation of 100% Flameless Oxyfuel:
Complete conversion of a Walking Beam Furnace at Outokumpu's Degerfors mill, Sweden in 2003.

30% Capacity Increase

30% Fuel Savings

REBOX® HLL – More than 30 Installations

No full conversion, but more capacity and less fuel consumption

Picture from Masteel, China: Slabs heated with REBOX HLL in a 300 t/h Walking Beam Furnace

REBOX HLL is in operation in two 300 t/h Walking Beam Furnaces at SSAB in Sweden

Add-on system, typically put in the pre-heating and/or heating zones

15-30% lower fuel consumption and CO_2 emissions, lower NOx emissions

Recently Commissioned:

- Jindal Stainless, India
- Celsa, Norway
- Amsteel, Malaysia
- ArcelorMittal, Germany

To be Commissioned:

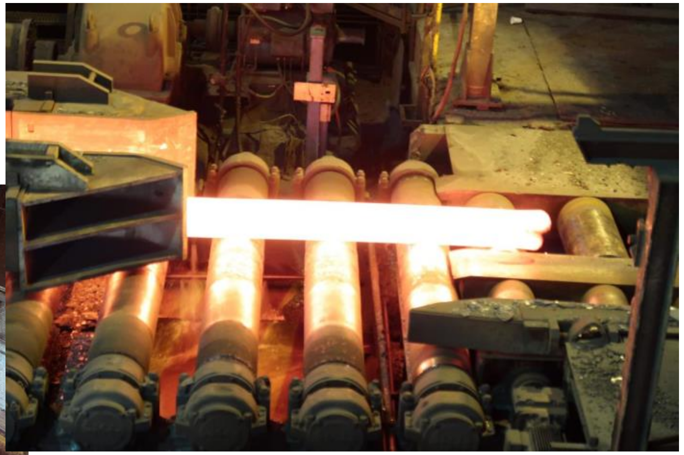
- Masteel, China (3 furnaces)
- Outokumpu, Sweden
- ArcelorMittal, Germany

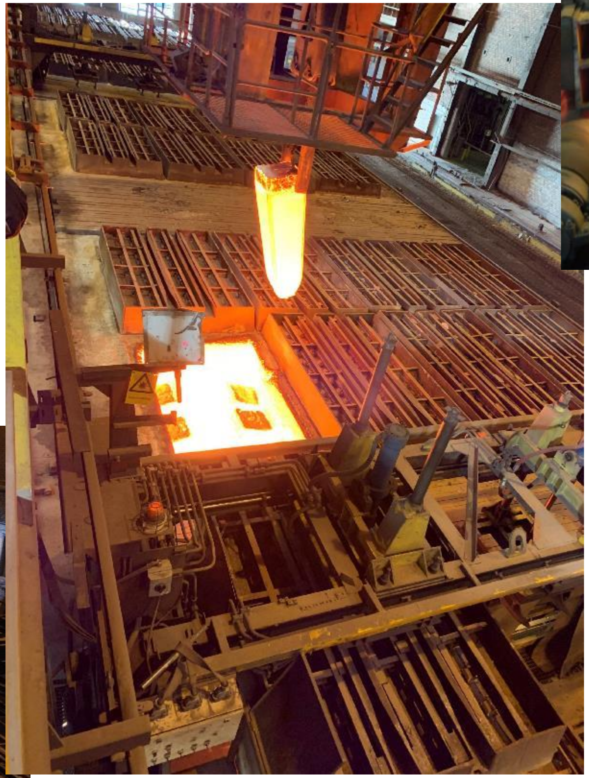
World's First Fossil Free Heated Steel

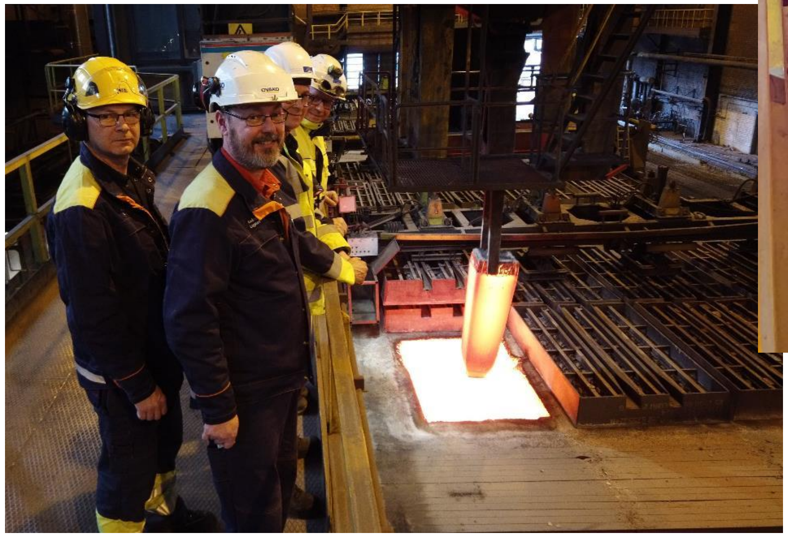
Ovako Steel, Hofors, Sweden
18th of March 2020

25 tons of ball bearing steel heated with Flameless Oxyfuel (REBOX® Hyox) using 100% Hydrogen as fuel

Both Hydrogen and Oxygen produced with Electricity from Renewable Energy sources







Full-scale permanent installation planned for 2023
24 Soaking Pit Furnaces
Saving 20,000 t CO_2 annually

H_2

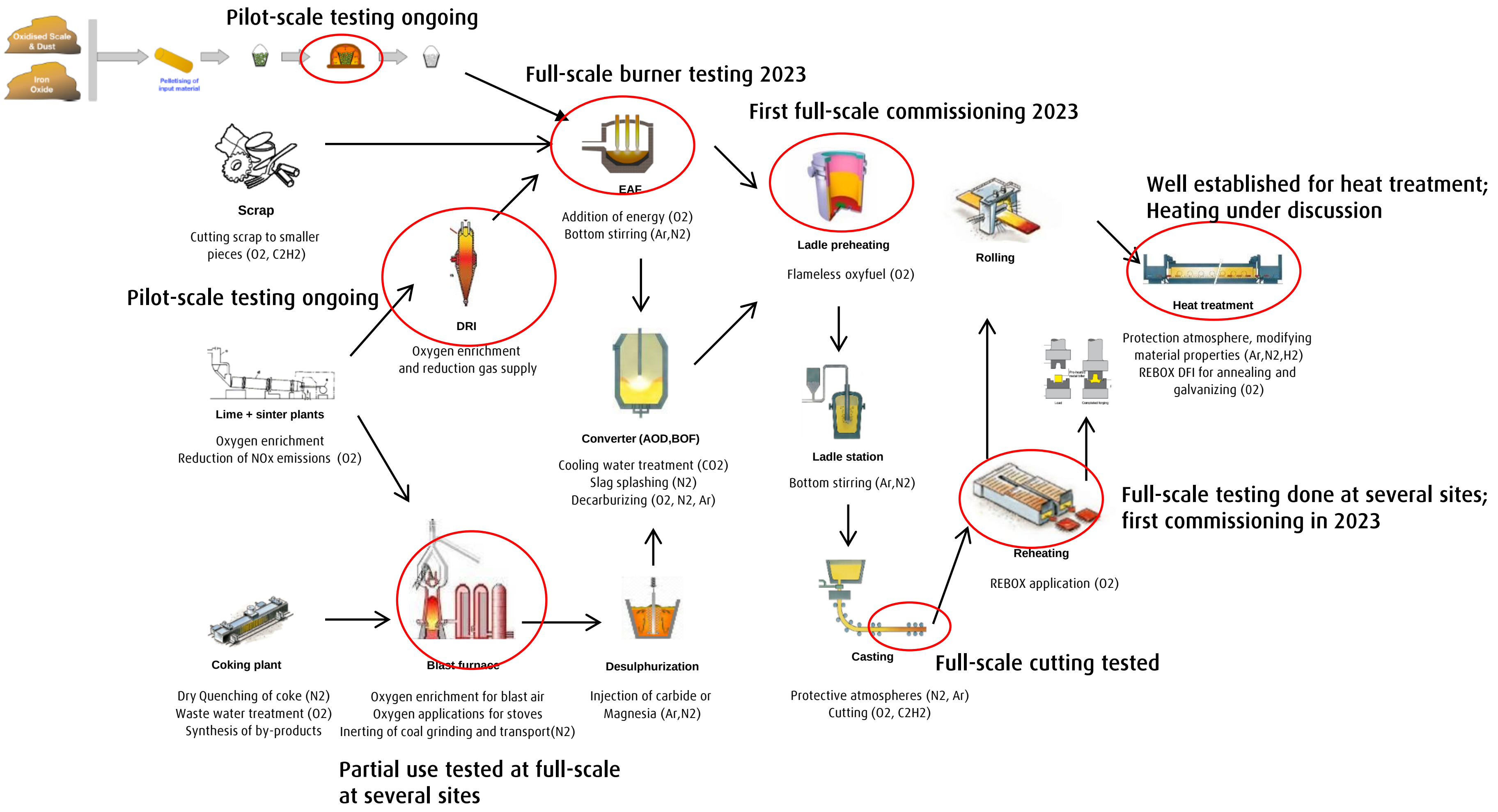
OXYGON® Flameless Oxyfuel Ladle Preheating
Ready for Using Hydrogen as Fuel

- Faster heating providing shorter heating cycles for less ladles in circulation
- 75-80% reduced flue gases due to less fuel and no nitrogen in combustion
- Up to 60% lower fuel consumption and CO_2 emissions
- More homogeneous heat distribution and improved temperature uniformity in the ladle
- Possibility to reach very high pre-heating temperatures if wanted (e.g., 1500ºC); a recent installation reported 20 kWh/t electricity savings in the EAF
- Ultra low NO_x emissions
- Can operate with H_2 or mixtures of H_2 and other fuels; <u>100% H_2 can give 100% reduction of CO_2 emissions.</u>

200+ OXYGON® Installations Worldwide

Hydrogen Use in the Steel Making Processes

Hydrogen Possibilities in Red

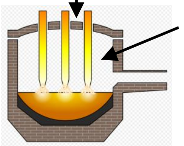


Hydrogen Requirements for Green Steel
The Importance of Increased Scrap Supply

X-Large Scale: From MW to GW

Minimill

Green power



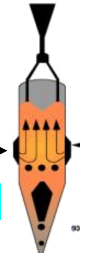
H2 CoJet

EAF

H2 Oxyfuel

Reheat Furnace

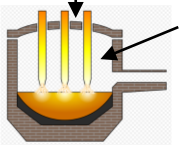
Integrated DRI Mill



Clean H2

DRI

Green power



H2 CoJet

EAF

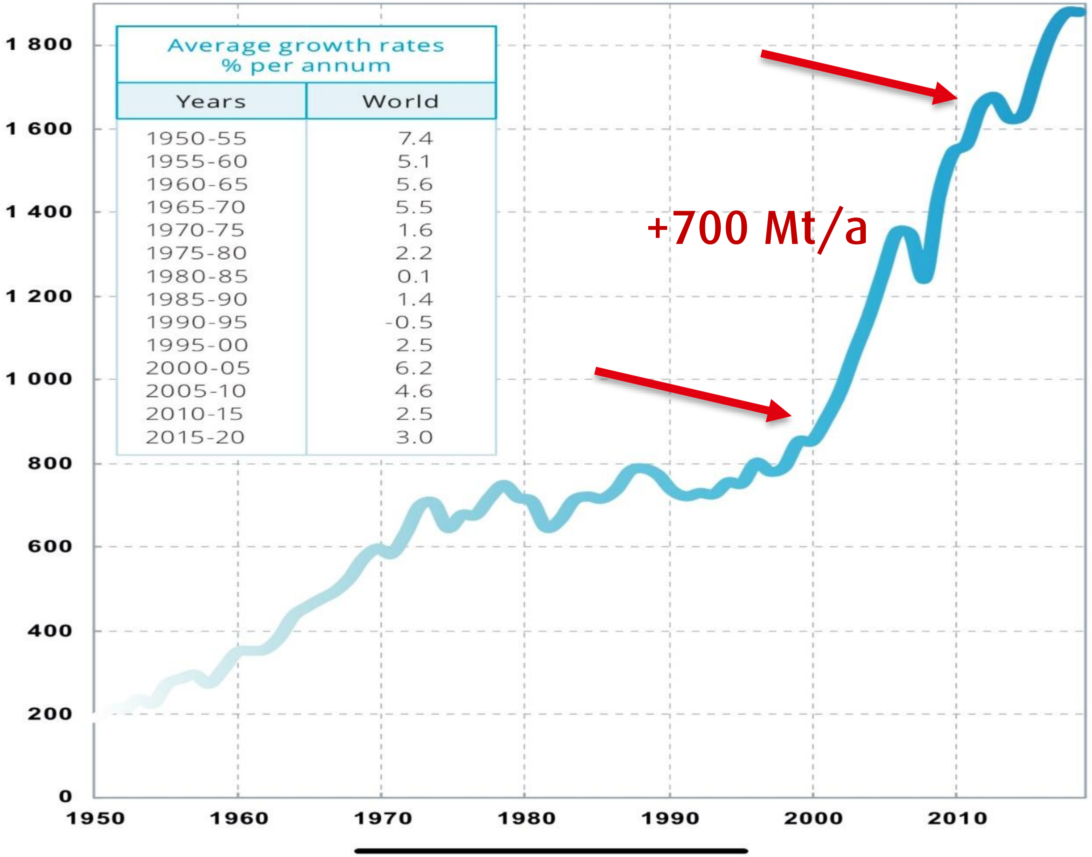
H2 Oxyfuel

Reheat Furnace

For 1 mm tpy production*

45 TPD H2 /
110 MW electrolyzer
+ 100 MW EAF power

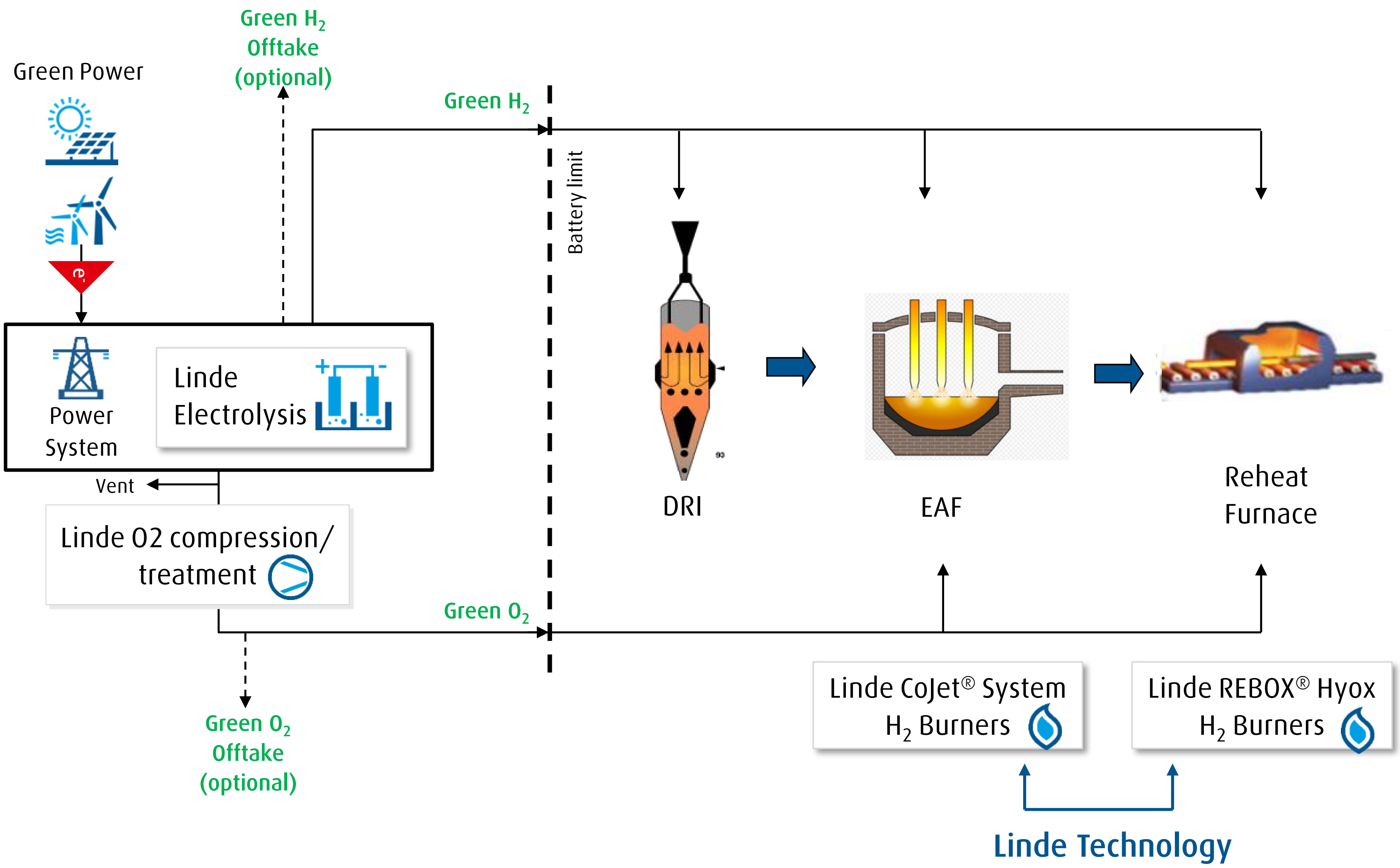
200 TPD H2 /
475 MW electrolyzer
+ 100 MW EAF power



*Rough estimates for a typical operation

Integrated Green Steel Production Ecosystem

DRI-EAF steel plant 2 Mt/y with 100% Green H_2 and O_2



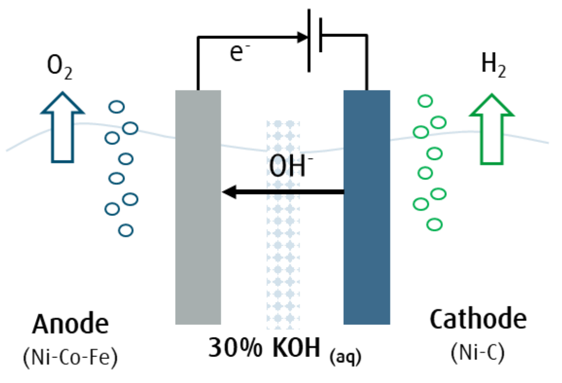
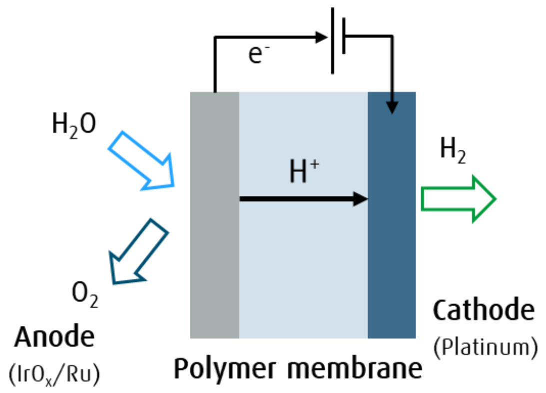
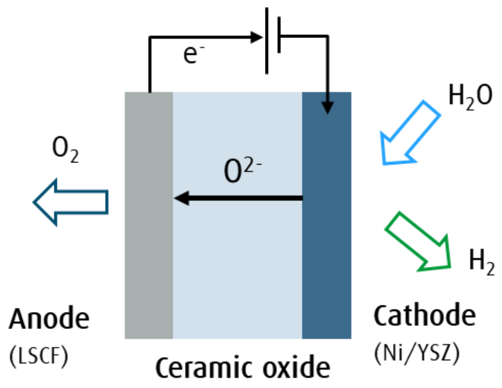
For full decarbonization of 2 Mt/y steel plant with 100% DRI:

H2 and O2 Production	
Electrolyzer capacity	1.1 GW
H2 Production	210,000 Nm3/h
O2 Production	100,000 Nm3/h

H2 and O2 Consumption per tonne of rolled steel				
	DRI	EAF	Reheat	Total
H2, kg/t	63	3	9	75
O2, kg/t	0-55	45	40	85-140

30% of electrolyzer O2 production is used, 70% potentially for other offtakers

Electrolysis Technologies

	Alkaline	Proton Exchange Membrane (PEM)	Solid Oxide (SOEC)
			
CAPEX (EPC)[1,2]	€ 600 / kW	€ 750 / kW	€ 900 / kW
EFFICIENCY	50-55 kWh/kg (up to 67%)	50-60 kWh/kg (up to 67%)	36-45 kWh/kg[3] (74-95%)
TEMPERATURE	70-90°C	55-80°C	600-850°C
PRODUCTS	H_2: 0 (30) bar; O_2: 0 (30) bar	H_2: 20-50 bar; O_2: 1-10 bar	H_2: 0 (5) bar; O_2: 0 (5) bar
STACK FEED	30% KOH	Water (ASTM Type II)	Steam
CURRENT DENSITY	0.2 – 1.2 A/cm2	0.5 – 3.0 A/cm2	0.2 to 1 A/cm2
Best For:	Cost, Scale, Maturity	Compact, Dynamic Response	Highest Efficiency

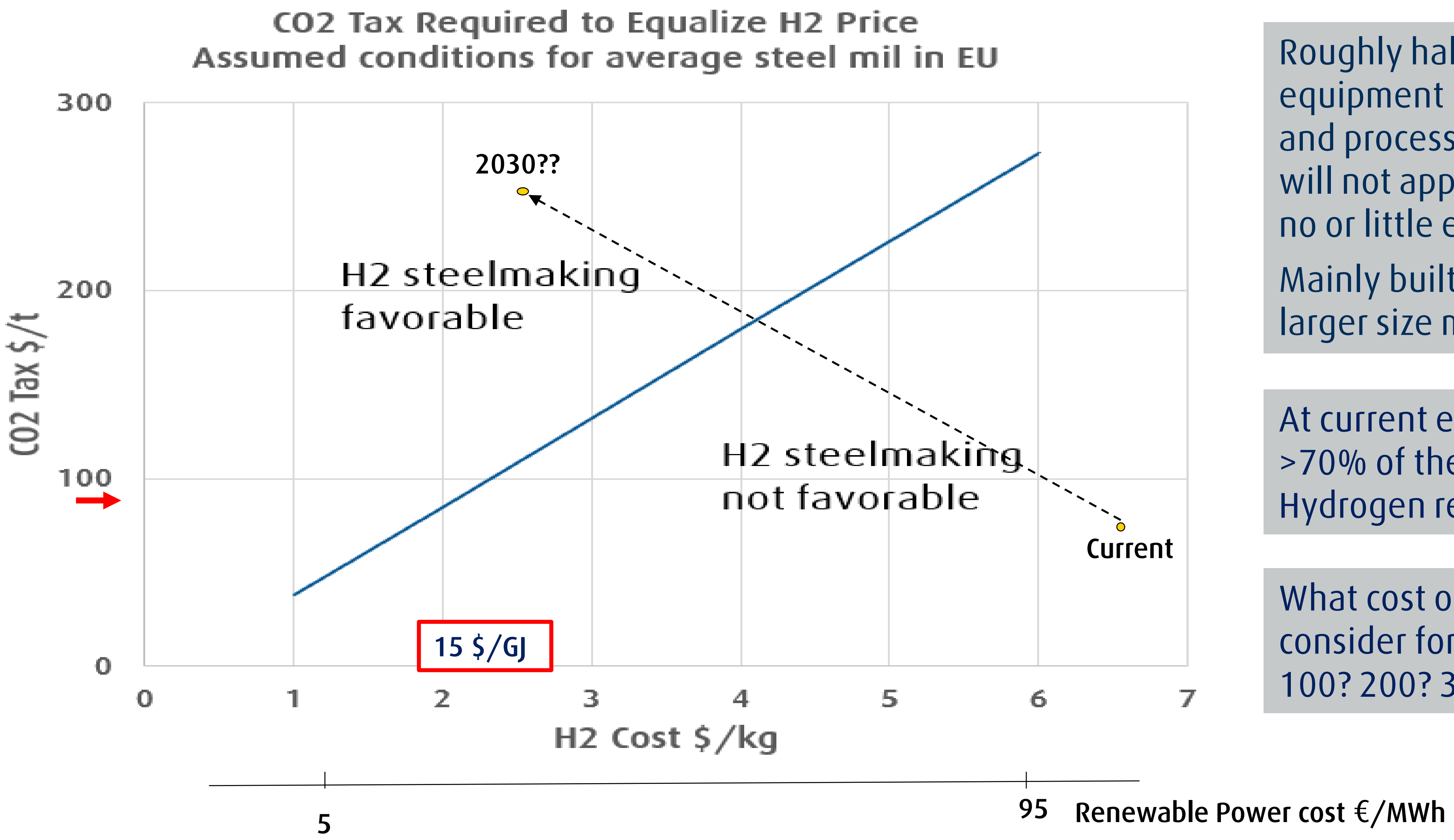
[1] 2025 projection; [2] to 30 barg; [3] depending on heat integration

Linde’s New PEM Electrolyzer Projects

Linde already operates 80+ electrolyzers

- 24 MW at Leuna, Germany (2022)
  Currently world’s largest PEM electrolyzer
- 24 MW at Porsgrunn, Norway (2023)
- 35 MW at Niagara, USA (2025)
- 2 x 100 MW at Lingen, Germany (2025)
- 100 MW at Wesseling, Germany

The Steel Decarbonisation Challenge
The Cost of Green Hydrogen in Europe



Roughly half of electrolyzers' equipment is 'standard' components and processes where Wright's Law will not apply as that part will have no or little elasticity of cost.

Mainly built on a modular concept; a larger size means more modules.

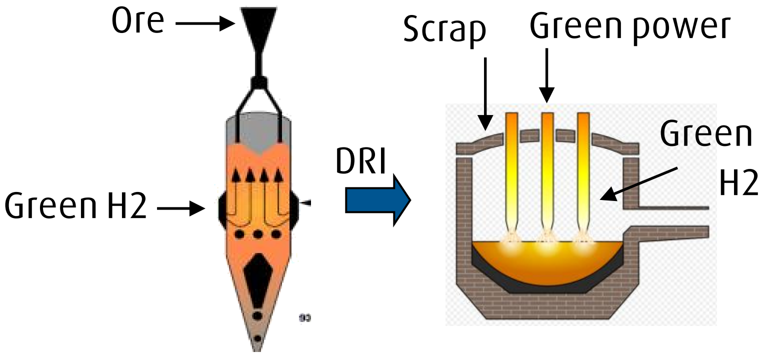
At current electricity prices in Europe, >70% of the cost to produce Green Hydrogen relate to electricity.

What cost of CO_2 emissions to consider for investment calculations? 100? 200? 300?

The Steel Decarbonization Challenge

Full Decarbonization Requires a New Processing Route

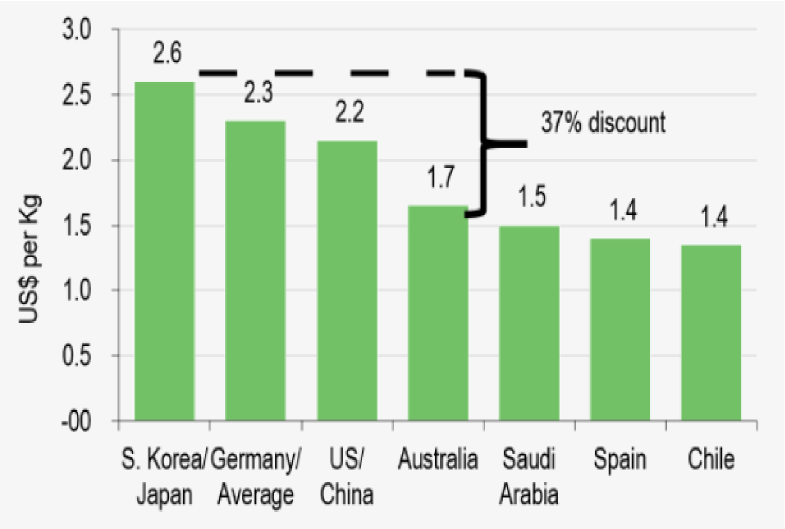
A full decarbonization of the steel industry would require at least a doubling of the current total world hydrogen production, corresponding to an increase of the Clean Hydrogen supply by about 200 times.



H2-DRI-EAF route offers near commercial route to decarbonization, but:

- CAPEX: Investment in DRI-EAF facilities (€1,000/t of capacity)
    - Investment increases 4-5x if we factor in CAPEX for upstream investments in Green Power (~ €4,000+/t)
- OPEX: Cost and Scale of Green H2
    - Mainly governed by cost of green electricity (>70% of cost in Europe)
    - 2 MM tpy plant requires 1 GW of green power
- Supply of DR Pellets – additional investments required; or use of BF Pellets or Fines
- Mismatch with size and pace of existing downstream facilities
- Carbon Capture & Storage: only feasible in certain geographical areas
- Steelmakers likely to maximize life of existing assets; phase out BFs at relining

Could Decarbonization Lead to Deindustrialization in Europe? Implementing Change when the World is Changing



Green H2 production costs by Country in 2030

H2 Council, McKinsey 2021

Required massively increased production of renewable power in Europe, as such challenged by NIMBY, will largely also need substantial investments in increased grid capacity.

"Europe has to Grow Out of the Mindset that its Problems are the World's Problems"

S. Jaishankar,

Indian Minister of External Affairs

Near-term Activities, Multiple Solutions, Long-term Development Projects

Carbon → Carbon Free

Near-Term (to ~2030)	Mid-Term (to ~2040)	Long-Term (to ~2050)
Pellets replacing sinter	Carbon Capture	Full use of hydrogen as a reductant
More charge of scrap and DRI	Low-carbon fuels	Hot end at renewable energy supply, cold end at market
Increased Energy-efficiency	Partial use of hydrogen as a reductant	Green Steel is the norm
Use of hydrogen as a fuel	Low Carbon Footprint Steel is the norm	
Carbon Footprint Certificates		

The pace will be different in different parts of the world. Viable supply of renewable power might be more pace-determining than technology.

Thank you for your attention!

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Making our world more productive

Linde