



# Development and Deployment of Oxyfuel-Hydrogen Solutions

4<sup>th</sup> Aachener Ofenbau- und Thermoprozess-Kolloquium  
Aachen, 17<sup>th</sup> – 18<sup>th</sup> of October 2023

Joachim von Schéele

Making our world more productive



# Linde – Gases and Technologies Supporting Green Production




## World's Largest Industrial Gases Company

- Sales at \$33 billion
- Market Capitalization at \$180 billion
- Activities in 100+ Countries
- 65,000 Employees
- 6,600+ Patents
- Investing >\$1 billion per year in Clean Energy
- Both Gases and Engineering (EPC)



## RECOGNITION

MEMBER OF  
**Dow Jones  
Sustainability Indices**

In collaboration with  or RobecoSAM brand



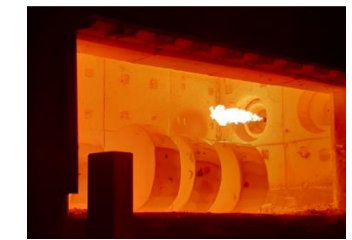
## World-leading Supplier of Hydrogen

- 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



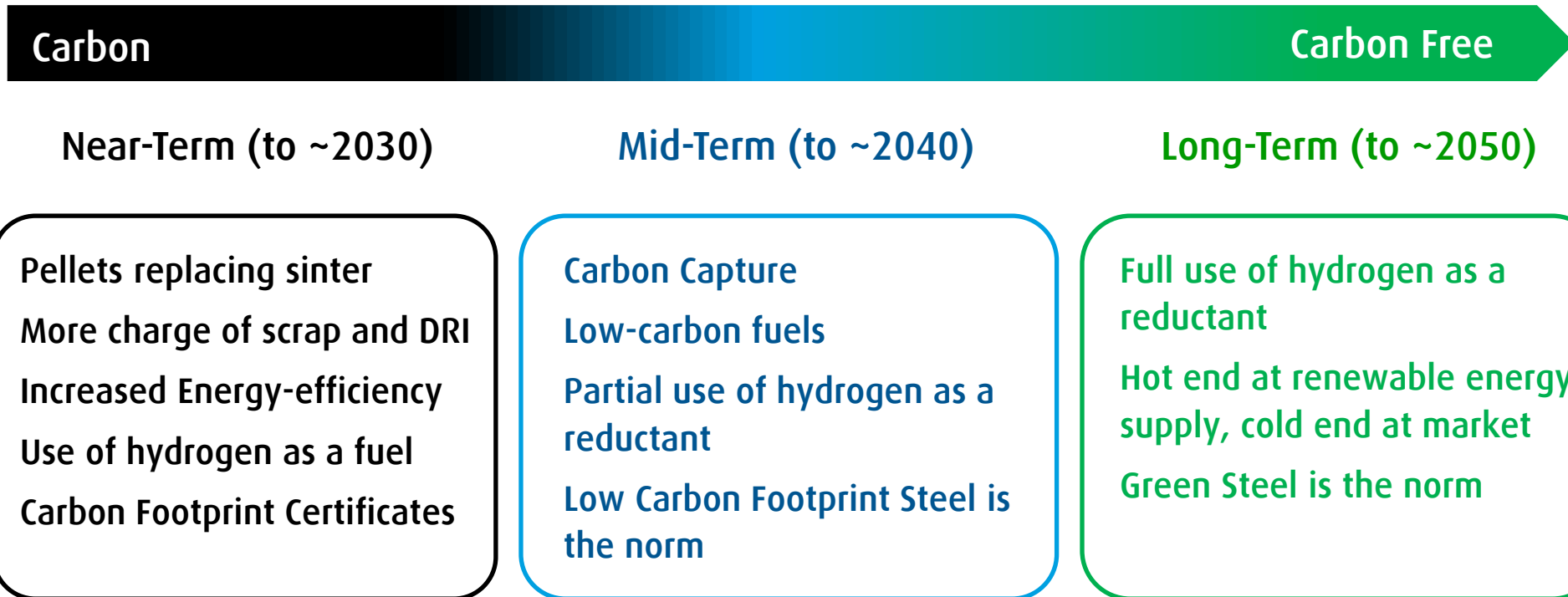
## Provider of Leading Technologies

- 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
- LTOF® 50+ installations in Aluminium Melting
- OPTIMELT® Heat Recovery Solutions for Glass Manufacturing



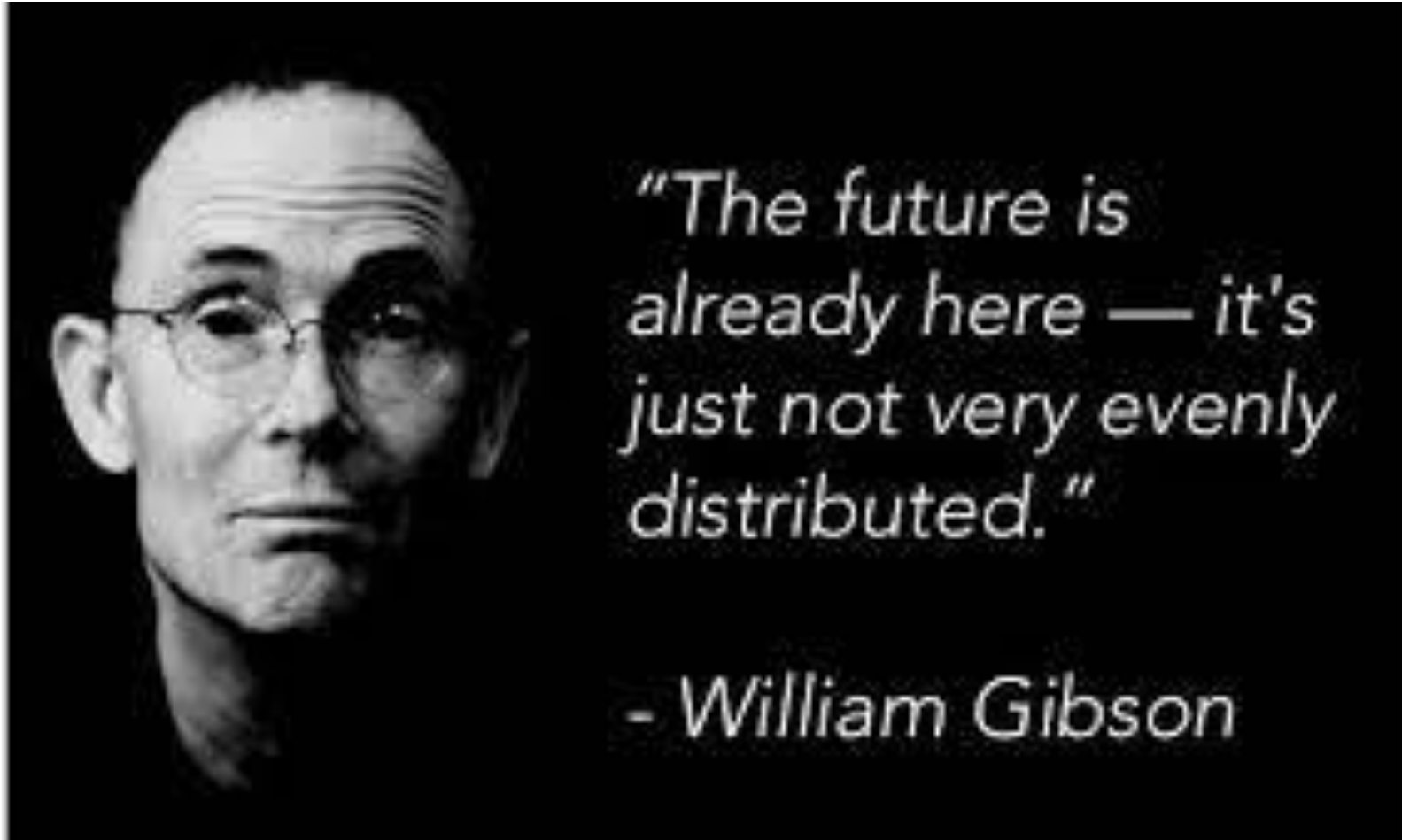
# Steel Industry Decarbonisation

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



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

# Solutions for Hydrogen as Fuel are Already Here, Ready to Be Used and Currently Being Implemented



# Linde's New PEM Electrolyzer Projects

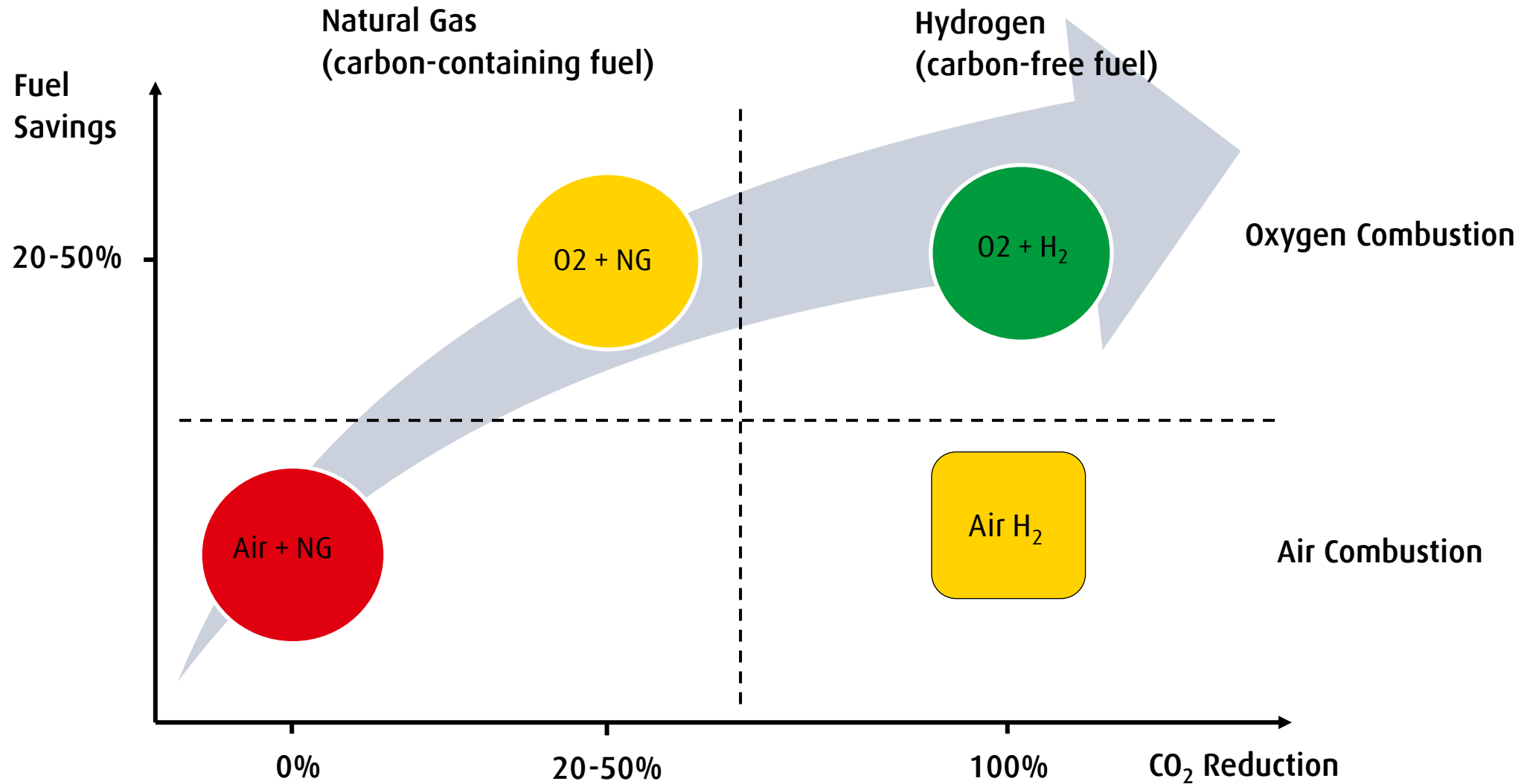


- ❑ 24 MW at Leuna, Germany  
Currently world's largest PEM electrolyzer
- ❑ 24 MW at Porsgrunn, Norway (2024)
- ❑ 35 MW at Niagara, USA (2025)
- ❑ 2 x 100 MW at Lingen, Germany (2025)
- ❑ 100 MW at Wesseling, Germany

Linde already operates 80+ electrolyzers

PEM electrolyzers in the range 25-100 MW will be in operation in the next few years.

# Route to Decarbonize Industrial Heating Operations



# Hydrogen Combustion Economics

## Oxyfuel is a Prerequisite for Hydrogen Combustion

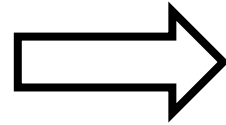


Hydrogen will be an expensive fuel

- Lowest anticipated cost of H<sub>2</sub> = €2/kg
- Equivalent to ~€15/GJ (\$15/MM BTU)

Oxyfuel Combustion will be economically necessary with H<sub>2</sub> fuel

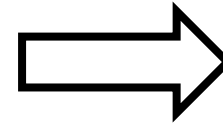
**Air-fuel**



**Oxyfuel**

20-60%

CO<sub>2</sub> Savings



**Oxyfuel w/ H<sub>2</sub>**

Full

Decarbonisation

Furnace atmosphere

~15% H<sub>2</sub>O(g)

~55% H<sub>2</sub>O(g)

~95% H<sub>2</sub>O(g)

# To Date Linde has Made Trials with Hydrogen Combustion in the Following Industries



➤ **Steel**

Supplying up to 3,500  
Nm<sup>3</sup>/h for two weeks

➤ **Aluminium**

➤ **Glass**

Several more onsite tests are now  
planned in various industries

➤ **Cement**



# Linde Technology Centre Munich Hydrogen Trials Spring 2019



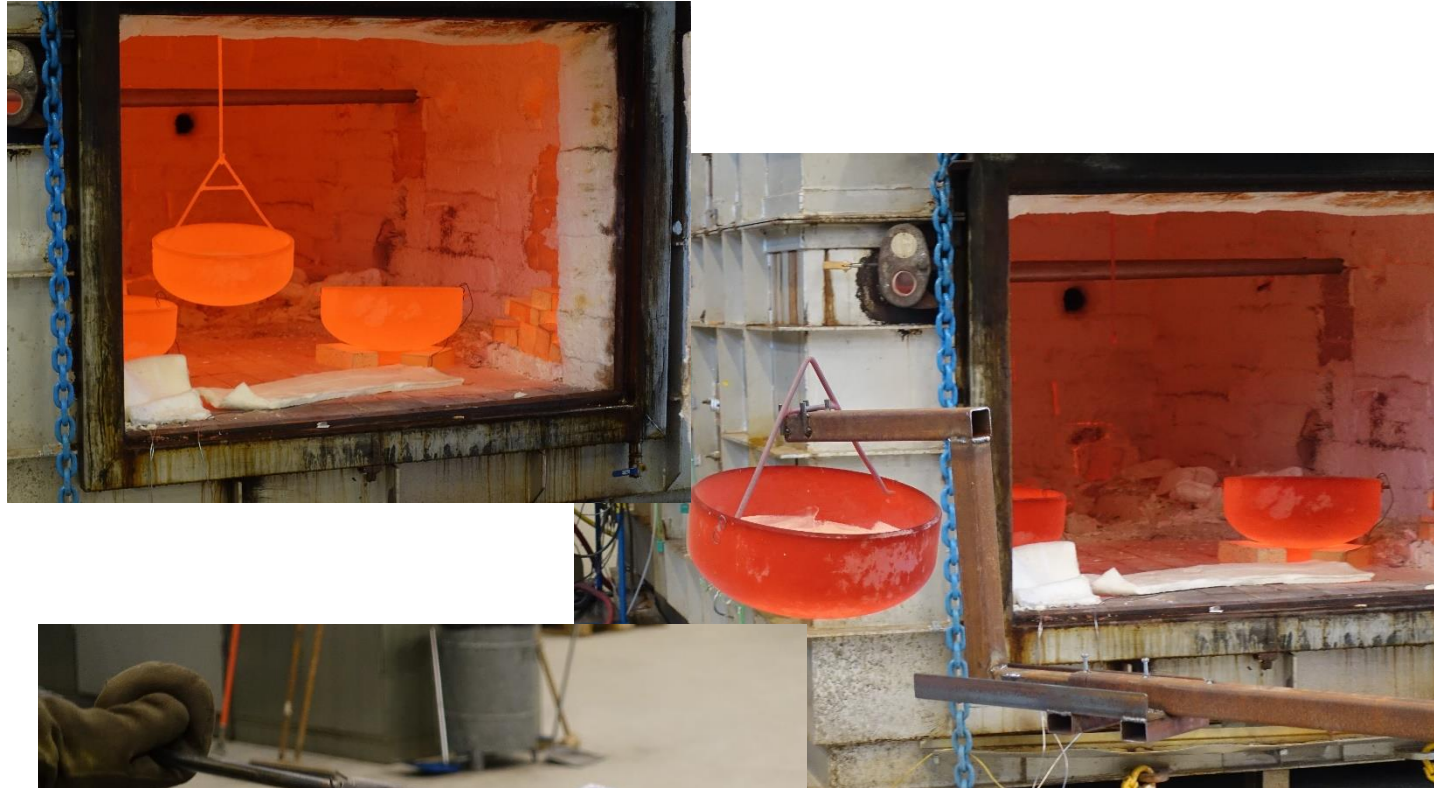
Open air firing of 300 kW COROX burner for Glass melting



High concentration of Water Vapour creates infrared radiation

# Aluminium Melting

## Low-Temperature Oxyfuel (LTOF) with 100% Hydrogen



To evaluate the consequences of H<sub>2</sub>-combustion, Linde together with Alcoa, Benteler, Hydro, Real Alloy, Speira, and Sintef carried out multiple series of tests. Melting and holding 10 kg samples of 5xxx and 6xxx alloys in various atmospheres using LNG, H<sub>2</sub> and mixtures thereof as fuel.

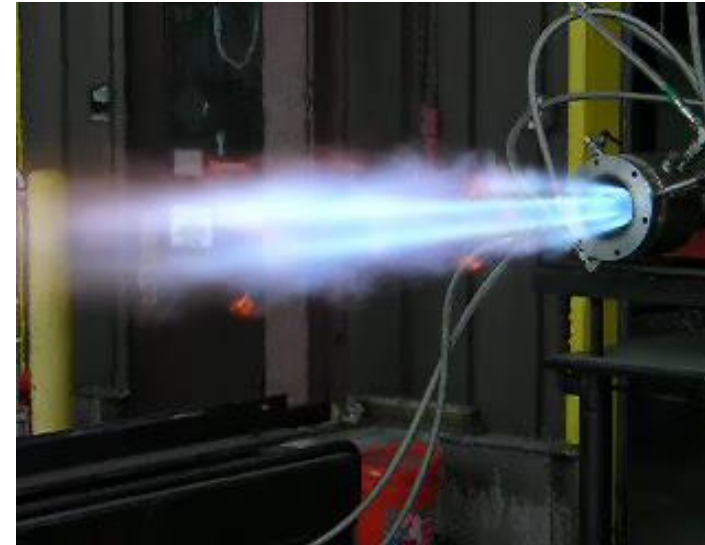
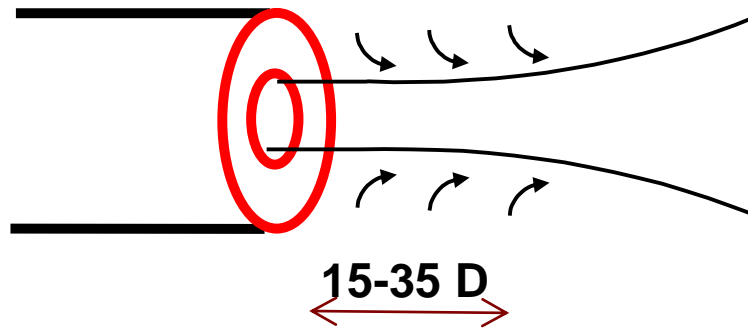
Evaluation of the results indicate no increased oxidation and no negative impact on the final product.

# CoJet<sup>®</sup> Coherent Jet Technology

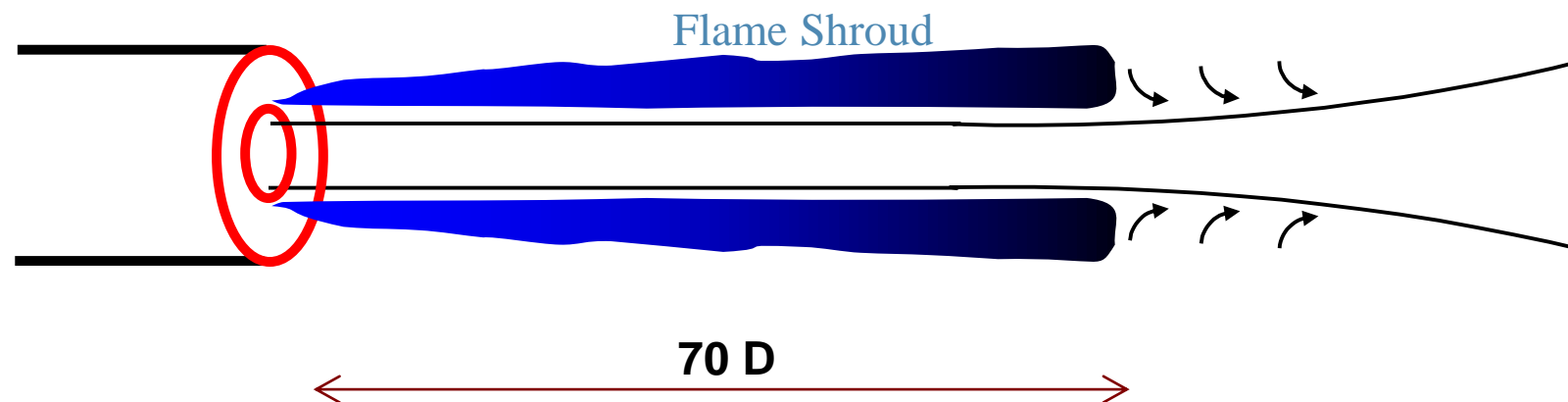
Revolutionized Electric Arc Furnace Steelmaking since 1996



## ● Supersonic Jet



## ● Coherent Jet



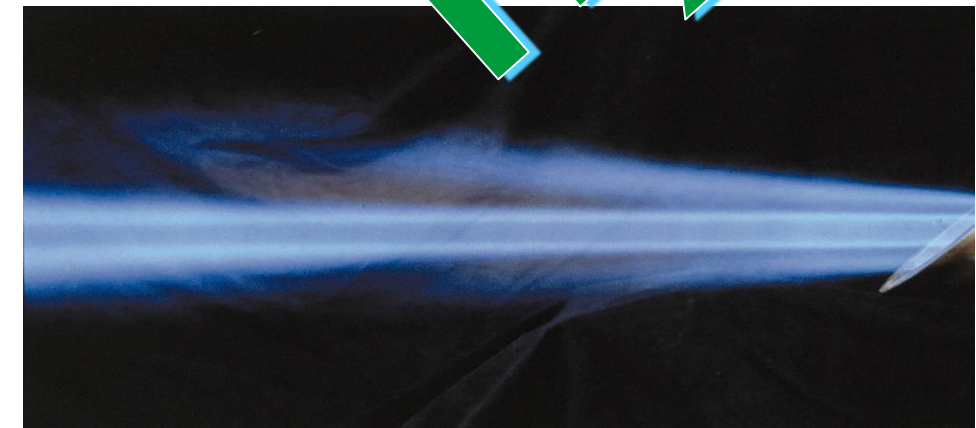
# CoJet® Coherent Jet Technology – 170+ Installations

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

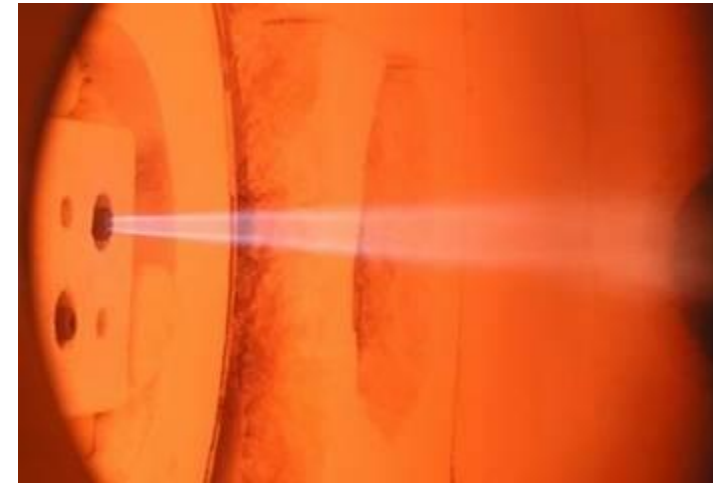
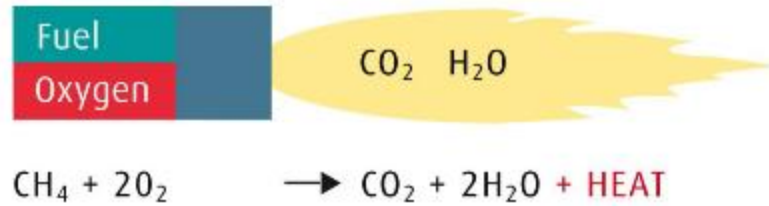


It has been demonstrated that Hydrogen is the best fuel for CoJet, producing the longest jets!

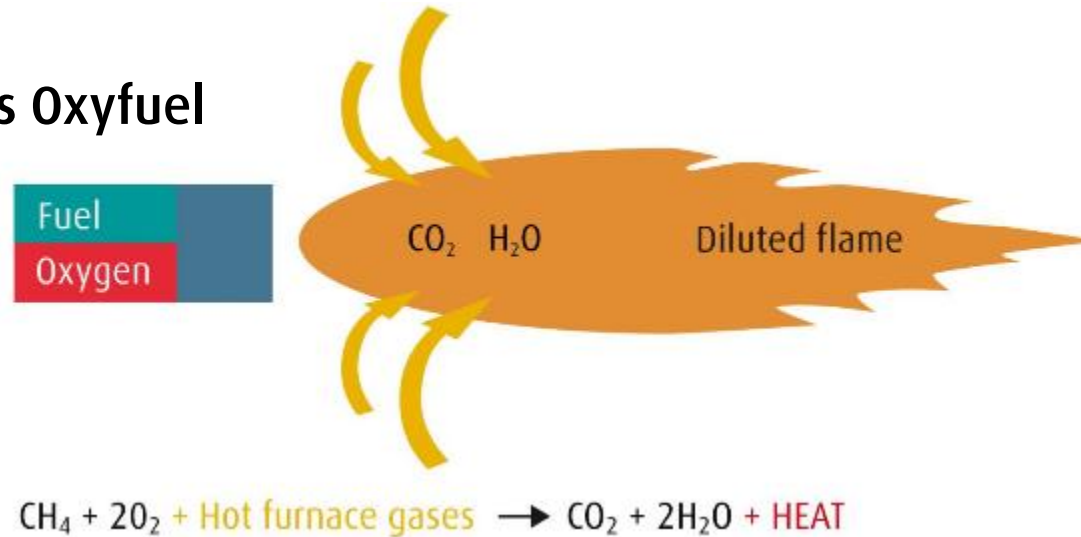
# Conventional Oxyfuel and Flameless Oxyfuel



## Conventional Oxyfuel



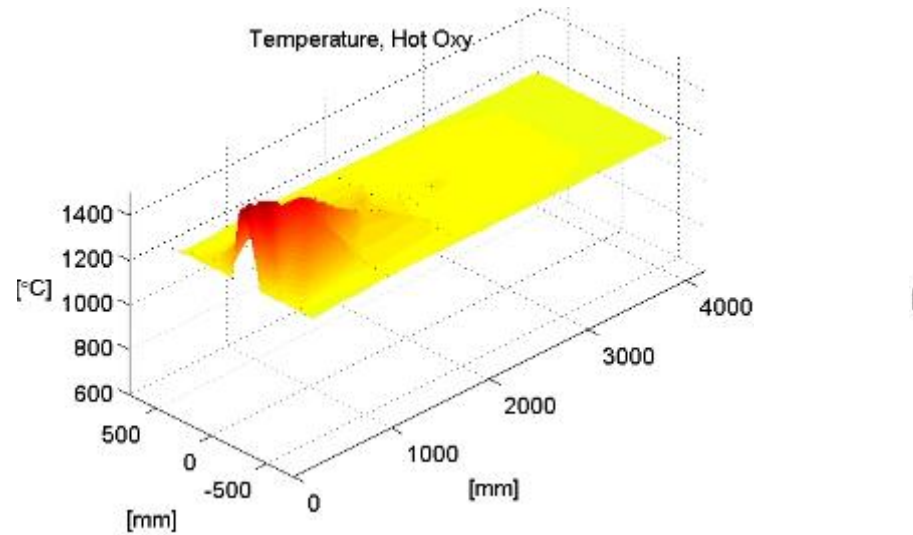
## Flameless Oxyfuel



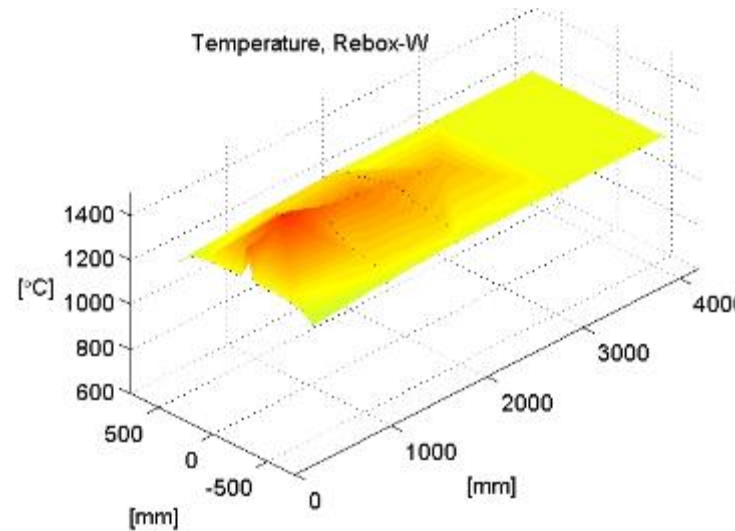
# Flame Temperature Profiles of Conventional Oxyfuel and Flameless Oxyfuel



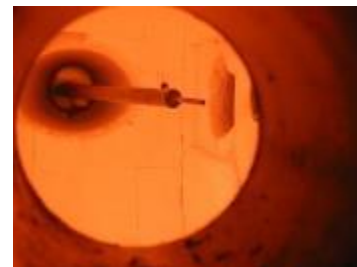
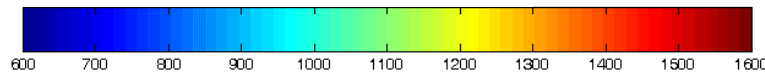
Data from evaluation by Royal Institute of Technology (KTH), Sweden; furnace at 1200°C



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<sup>®</sup> 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<sub>2</sub> Emission by up to 50%, by 100% with H<sub>2</sub>
- Reduction of NO<sub>x</sub> Emission
- Improved temperature uniformity, <5°C
- Decrease of Scaling Losses by up to 50%

# REBOX® Oxyfuel Solutions in Steel Reheating and Annealing

## 180+ Installations at 40+ Steel Mills



### REBOX Oxyfuel Installations:

- In total 184 to date
- Thereof 26 as REBOX HLL (hybrid solution)
- 30 in stainless steel production
- 12 in new furnaces
- 24 in Walking Beam Furnaces





# REBOX® Installations at Outokumpu



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

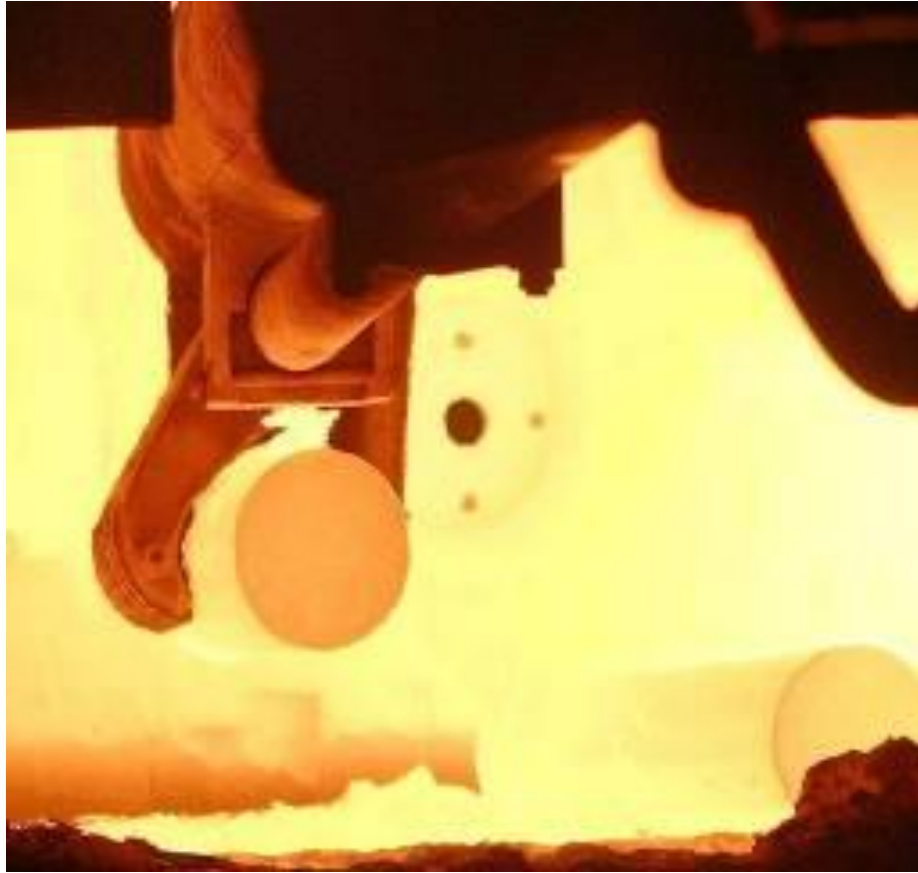


**30% Capacity Increase**

**30% Fuel Savings**



# Flameless Oxyfuel with Hydrogen as Fuel Burner Testing and Development to Secure Benefits



**Natural Gas fired Flameless Oxyfuel at Rotary Hearth Furnace for Tube Production at ArcelorMittal**



**Hydrogen fired Flameless Oxyfuel at a Linde Technology Centre, Stockholm**

# Potential Issues of Using Hydrogen Instead of Natural Gas or LPG at Steel Reheating



- Safety
- Temperature Profile in the Furnace
- Generation of NO<sub>x</sub>
- Water Content in Flue-gas
- Flue-gas Analysis
- Impact on Refractory Lining
- Scale Formation (surface oxidation)
- Decarburization
- Hydrogen Pick-up

# Steel Reheating Tests with REBOX<sup>®</sup> Hyox Linde Technology Centre Stockholm, October 2019



Material tested from four steel companies, including engineering steel and stainless steel grades

# World's First Fossil Free Heated Steel



Ovako Steel, Hofors, Sweden  
18<sup>th</sup> of March 2020

25 tons of ball bearing steel heated with  
Flameless Oxyfuel using 100% Hydrogen  
as fuel

Both Hydrogen and Oxygen produced with  
Electricity from Renewable Energy sources

**OVAKO**



Full-scale permanent installation  
in Q4 2023

24 Soaking Pit Furnaces

Saving 20,000 t CO<sub>2</sub> annually



# REBOX<sup>®</sup> Installations at Alleima

## Soaking Pit Furnace with 100% Flameless Oxyfuel



Full-scale tests over three batches of stainless steel heated with Flameless Oxyfuel using 100% Hydrogen as fuel, took place at Alleima at Sandviken, Sweden in the autumn of 2022.

Both Hydrogen and Oxygen produced with Electricity from Renewable Energy sources.



# REBOX<sup>®</sup> Installations at Ovako Steel

2023 Conversion into 100% Full Flameless Oxyfuel at Imatra, Finland



75 t/h Walking Beam Furnace  
for Reheating of Blooms



25% Less Fuel Consumption

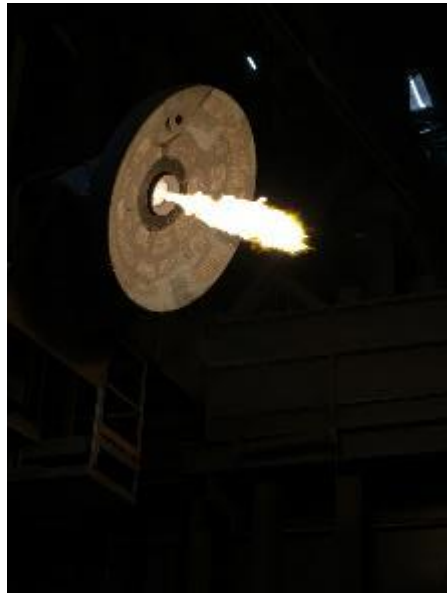
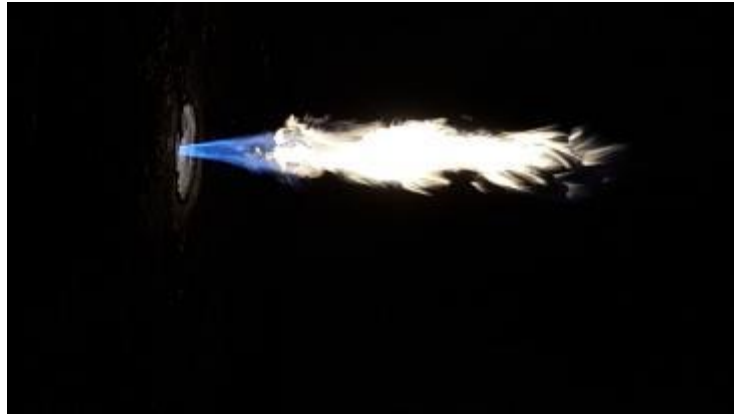
50% Less NOx Emissions

A Hydrogen Ready System



# OXYGON<sup>®</sup> Flameless Oxyfuel Ladle Preheating

## 200+ Installations Worldwide





# OXYGON<sup>®</sup> Flameless Oxyfuel Ladle Preheating

## Ready for Using Hydrogen as Fuel



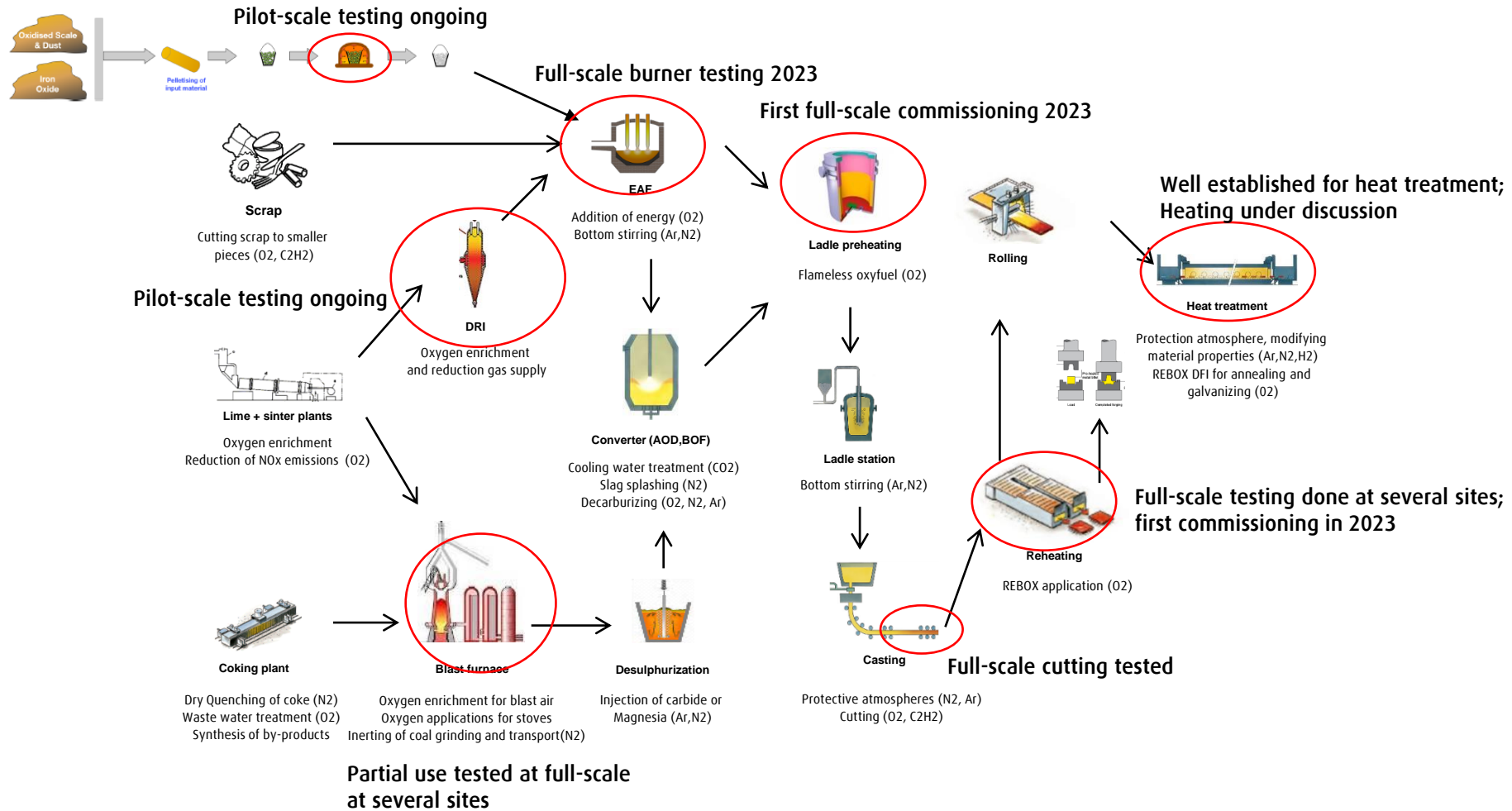
- Faster heating providing shorter heating cycles for less ladles in circulation
- 75-80% reduced flue gases due to less fuel and no nitrogen in combustion
- Up to 60% lower fuel consumption and CO<sub>2</sub> emissions
- More homogeneous heat distribution and improved temperature uniformity in the ladle
- Possibility to reach very high pre-heating temperatures if wanted (e.g., 1500°C); a recent installation reported 20 kWh/t electricity savings in the EAF
- Ultra low NO<sub>x</sub> emissions
- Can operate with H<sub>2</sub> or mixtures of H<sub>2</sub> and other fuels; 100% H<sub>2</sub> can give 100% reduction of CO<sub>2</sub> emissions.



200+ OXYGON<sup>®</sup>  
Installations  
Worldwide

# Hydrogen Use in the Steel Making Processes

## Hydrogen Possibilities in Red



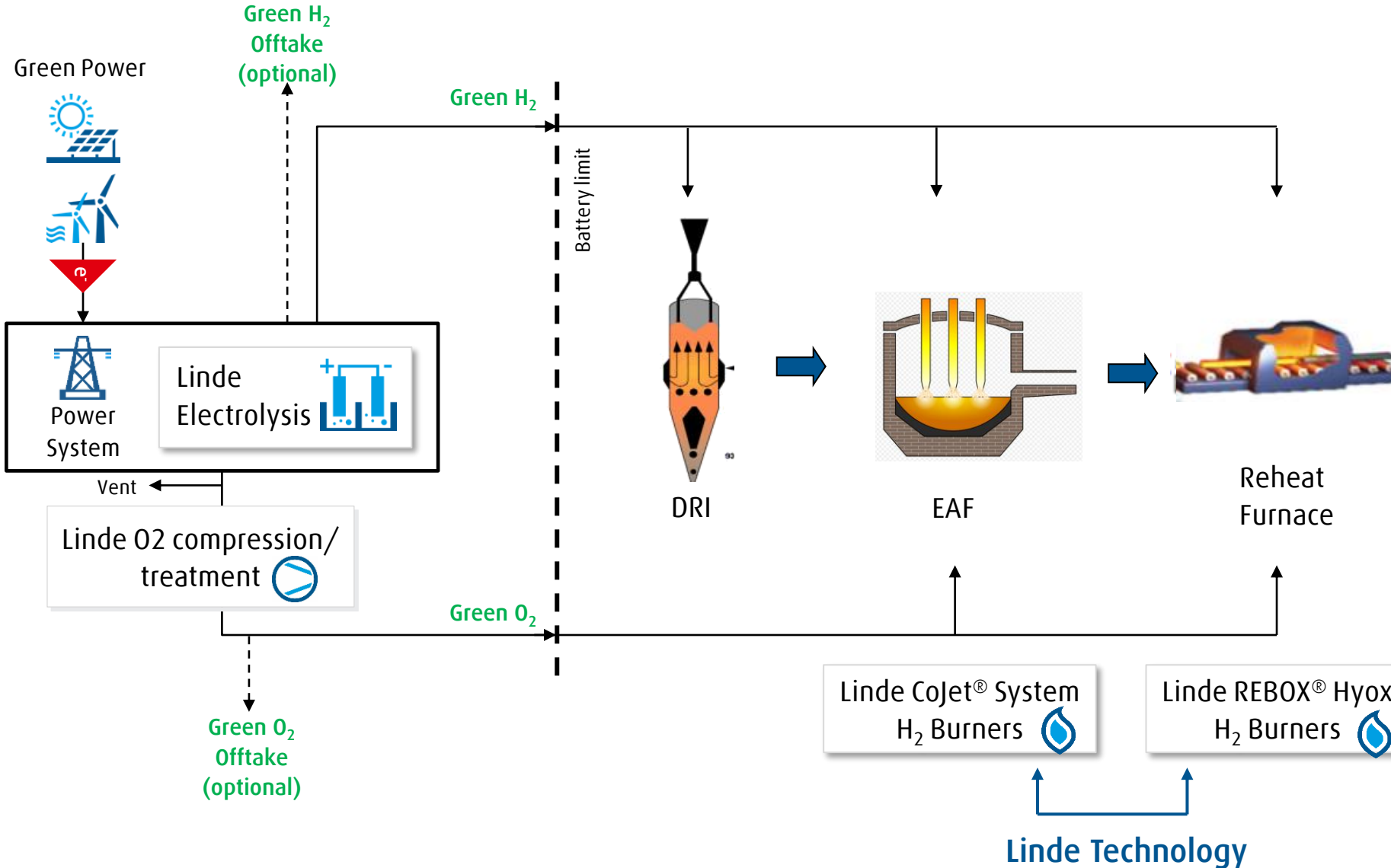
# Gas Cutting with Hydrogen at Continuous Casting of Stainless Steel



**Half the power and double the speed!**

# Integrated Green Steel Production Ecosystem

DRI-EAF steel plant 2 Mt/y with 100% Green H<sub>2</sub> and O<sub>2</sub>



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 Nm <sup>3</sup> /h
O2 Production	100,000 Nm <sup>3</sup> /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 O<sub>2</sub> production is used, 70% potentially for other offtakers

Linde Technology



Thank you for your attention!

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