



Successful Full-Scale Implementation of Hydrogen as a Fuel

Worldsteel Breakthrough Technology Conference

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Singapore, 2-3 December 2025



Linde Offerings for Decarbonisation



Hydrogen Supply

Blue H2
SMR/ATR...w/CCS



Green H2
Electrolysis



Ammonia &
methanol Plants



Liquefaction



Underground
storage



Pipelines



CO₂ Capture



Compression &
pretreatment



OASE © BLUE



HISORP © CC



Cryogenic
Separation



Logistics &
distribution



Storage (CCS)

Low Carbon Fuels

Linde's **Hot Oxygen Technology** produces **Syngas** from Biomass, MSW, Pyoil, Plastics, Coke Oven Gas, etc ...

Energy Efficiency

Oxyfuel burners and technology to convert from air-fuel ed to oxyfuel firing
Fuel savings, production increase and emissions reduction, hydrogen ready

Linde has Made Trials and Full-Scale Installations with Hydrogen Injection and Combustion in the Following Industries



➤ **Steel**

➤ **Glass**

➤ **Aluminium**

➤ **Non-ferrous Kilns**

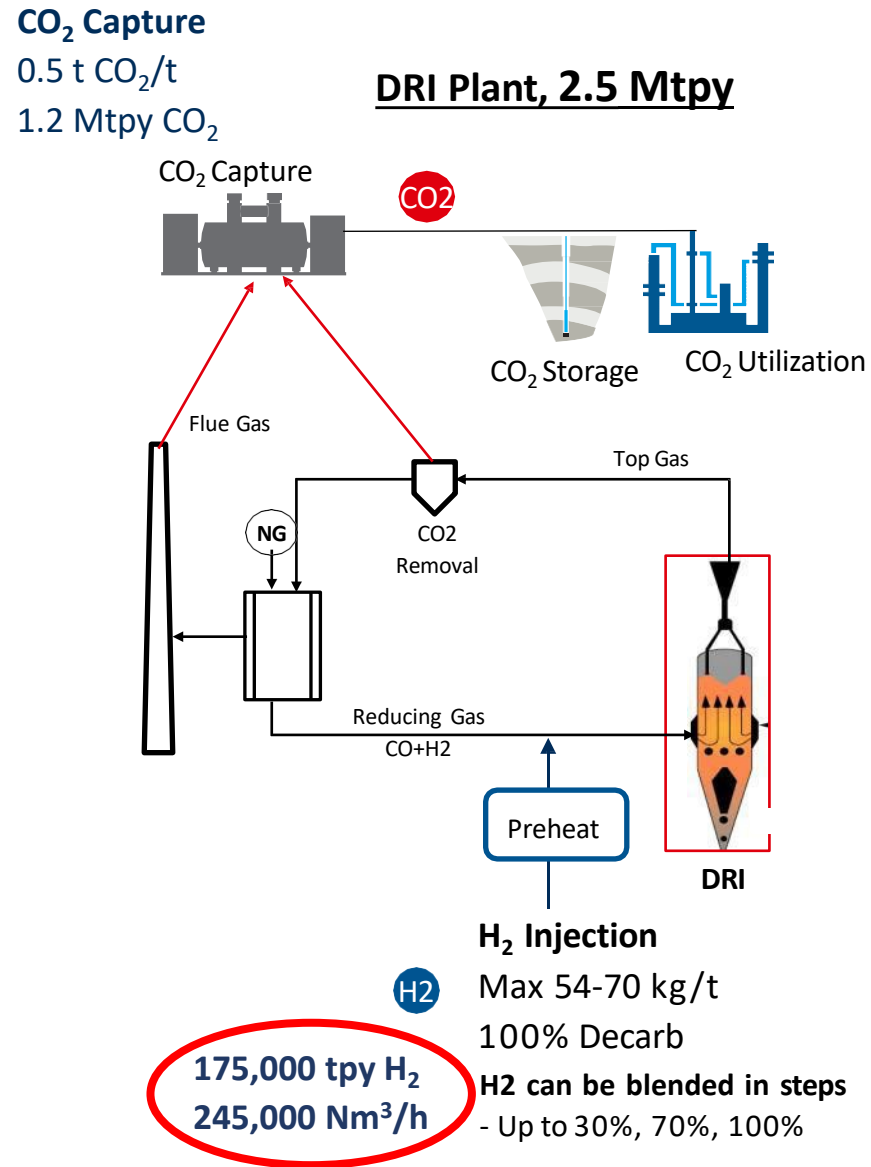
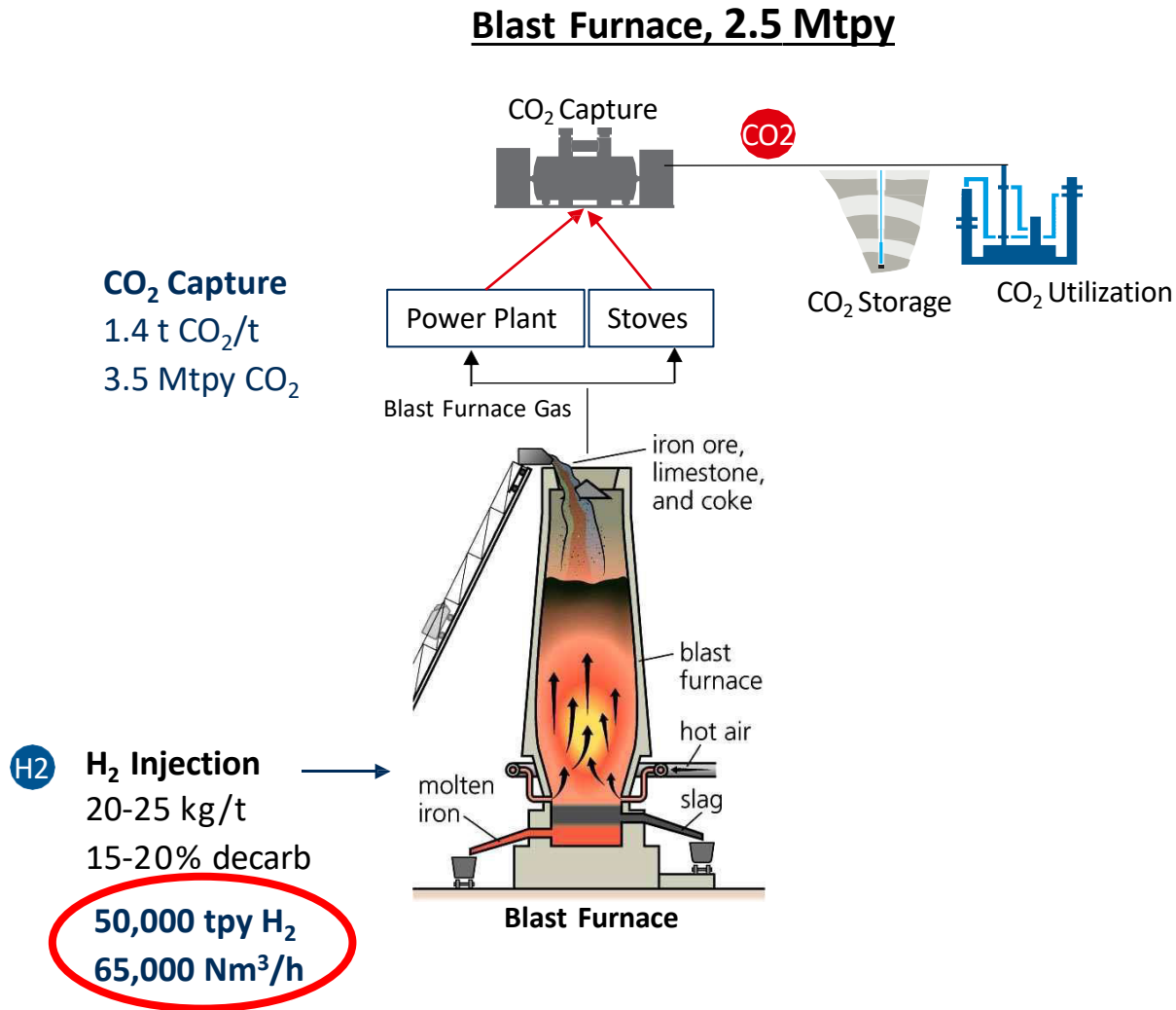
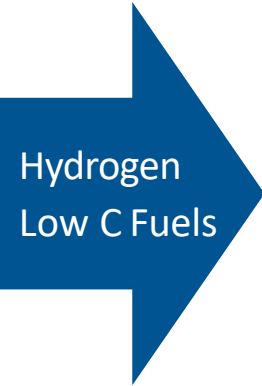
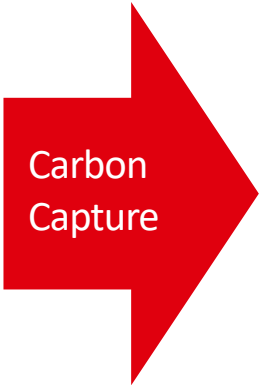
➤ **Cement**

Hydrogen supply at up to 3,500 Nm³/h for two weeks, shorter periods at 5,100 Nm³/h

Several more onsite tests are now planned in various industries

Decarbonisation Solutions for Ironmaking

Carbon Capture, Hydrogen, and Low Carbon Fuels are Primary Solutions



Trials with Hydrogen Injection in Blast Furnaces

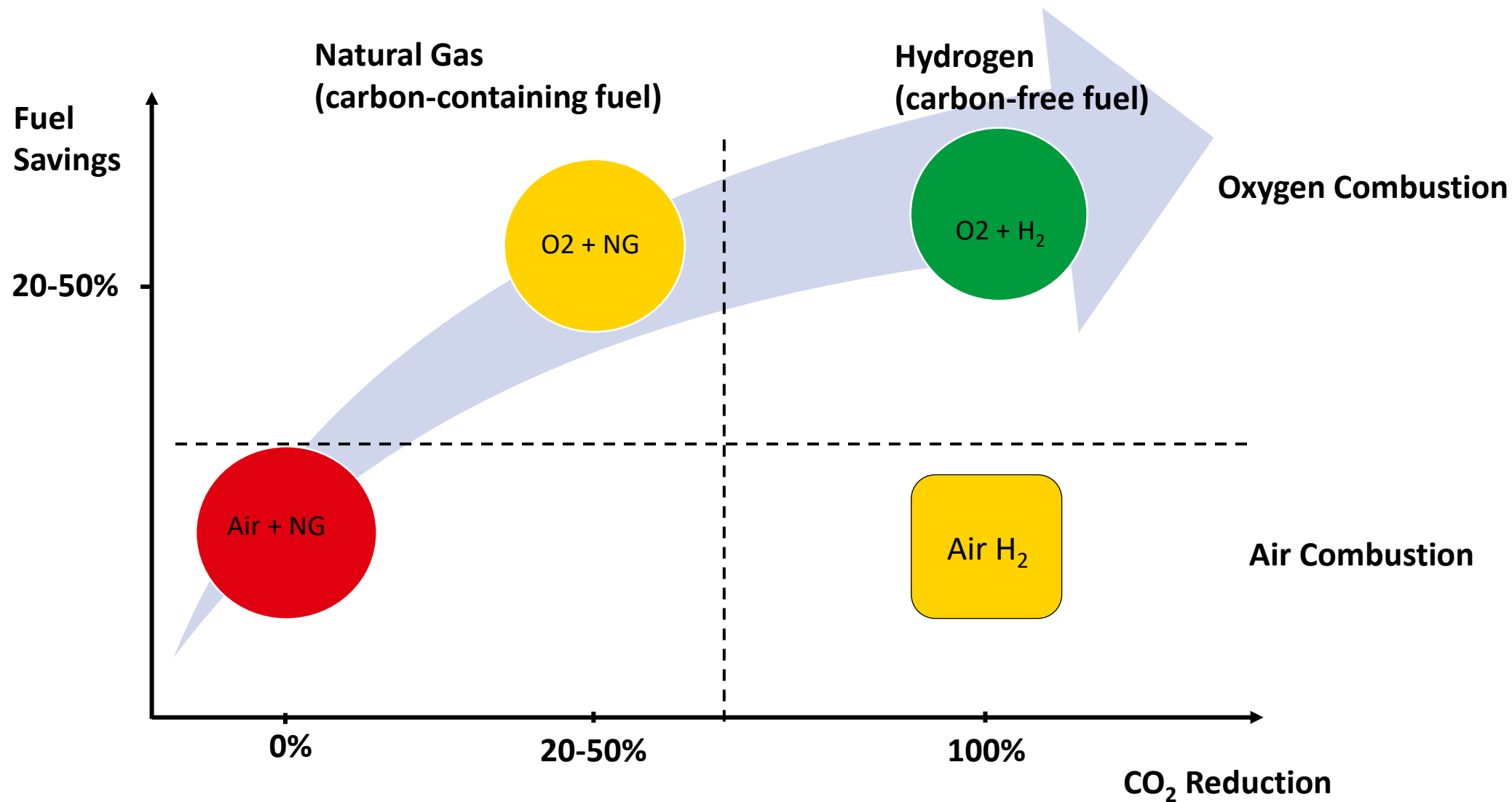


Linde partnered with customers to perform two successful trials injecting hydrogen into Blast Furnaces in 2024:

- Cleveland-Cliffs, USA: Injection into all 40 tuyeres, 0.6 kg H₂ per tonne hot metal
- Erdemir, Turkey: Injection into 4 tuyeres, 1.0 kg H₂ per tonne hot metal
- Hydrogen flow rates at 2,000 – 2,700 Nm³/h

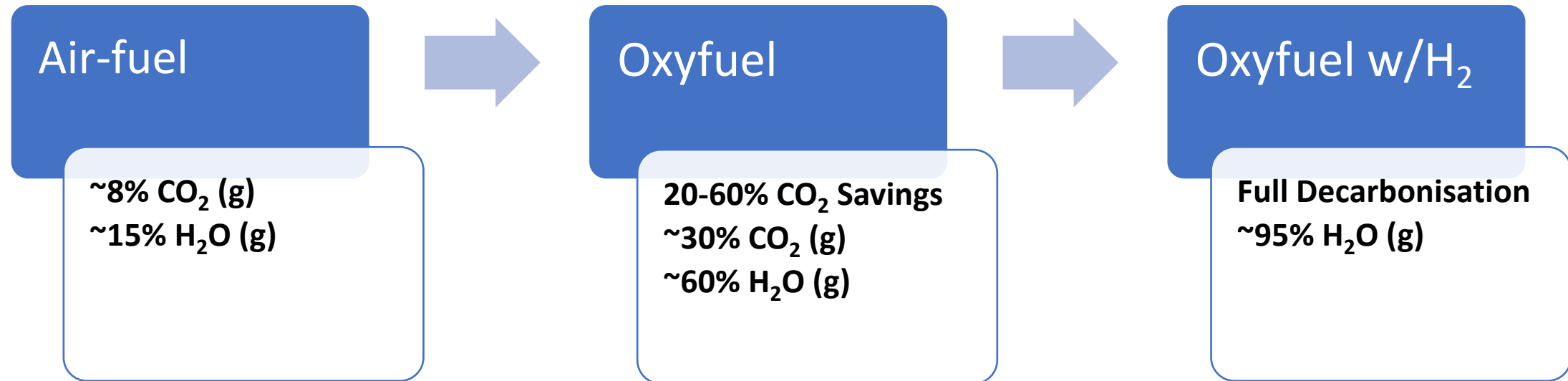


The Pathway to Decarbonize Melting and Heating Operations



Oxyfuel Solutions

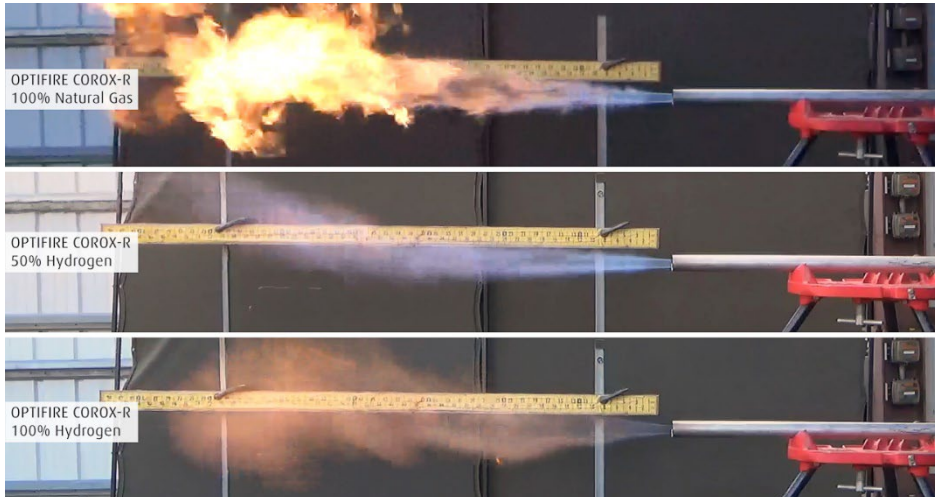
The Pathway to Decarbonization



Implementation of Oxyfuel supports Carbon Capture as it both substantially reduces the flue-gas volume down to about 25% and increases the concentration of CO₂.

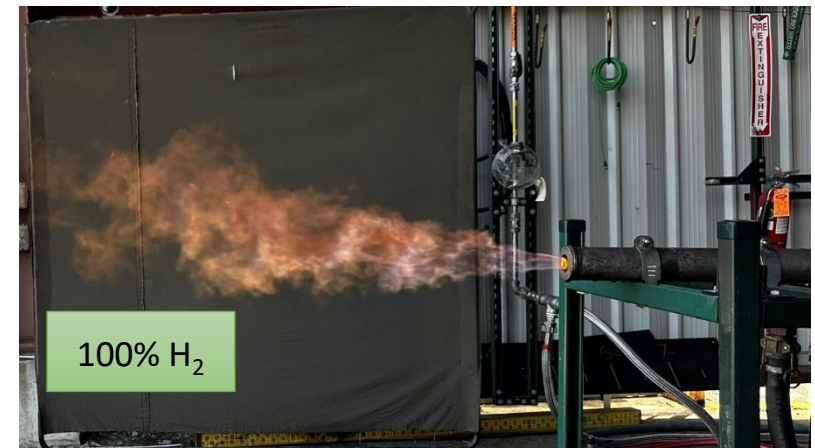
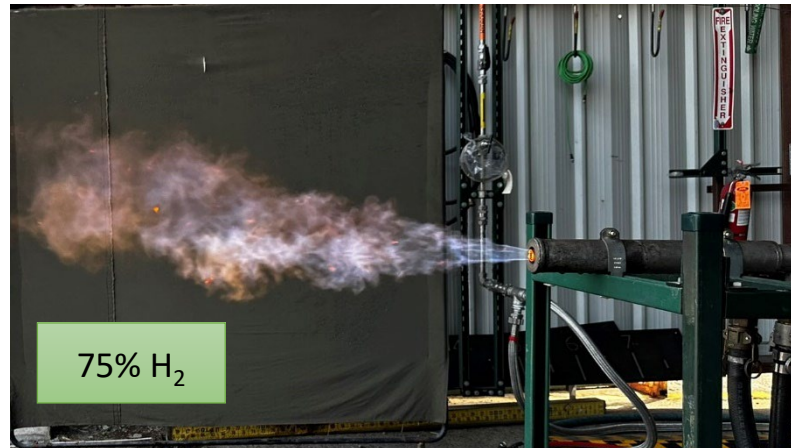
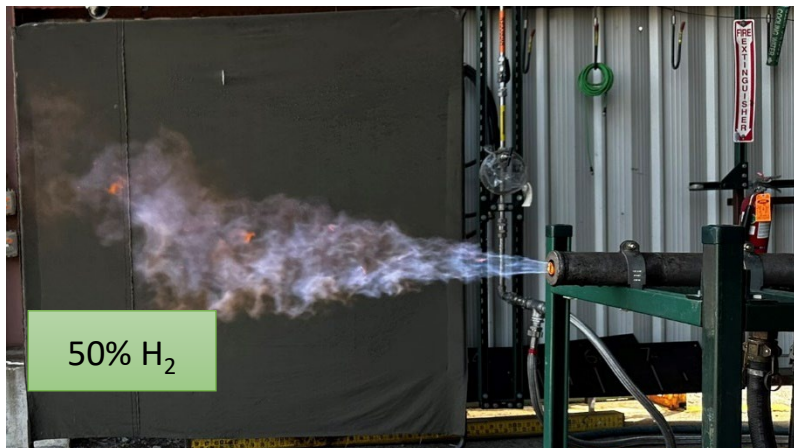
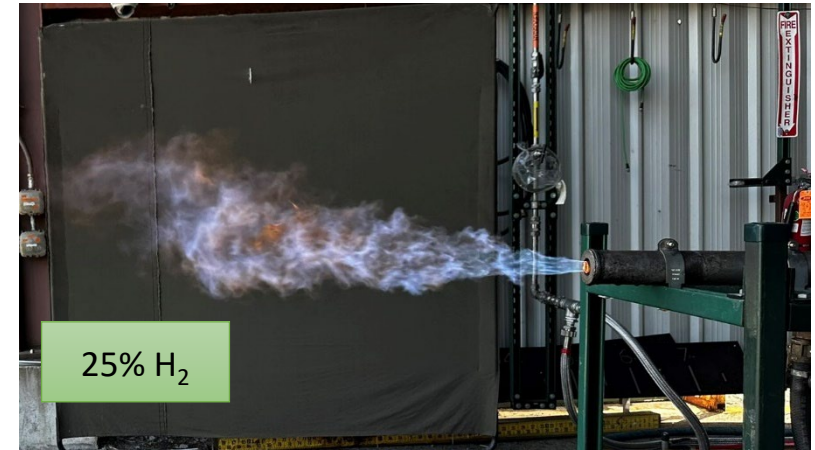
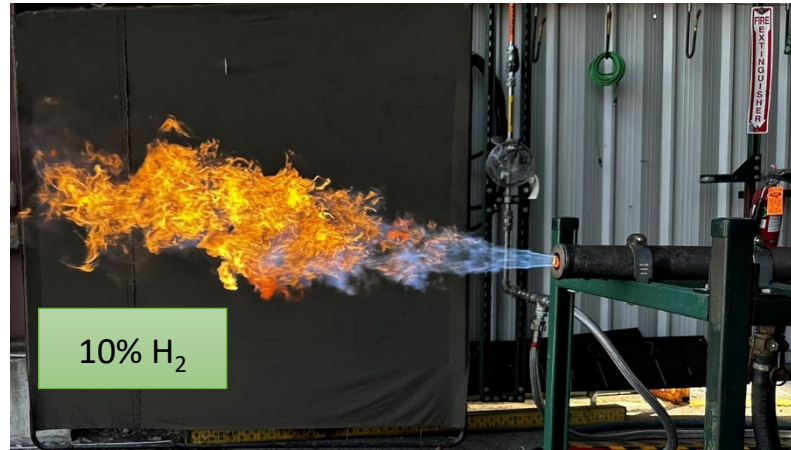
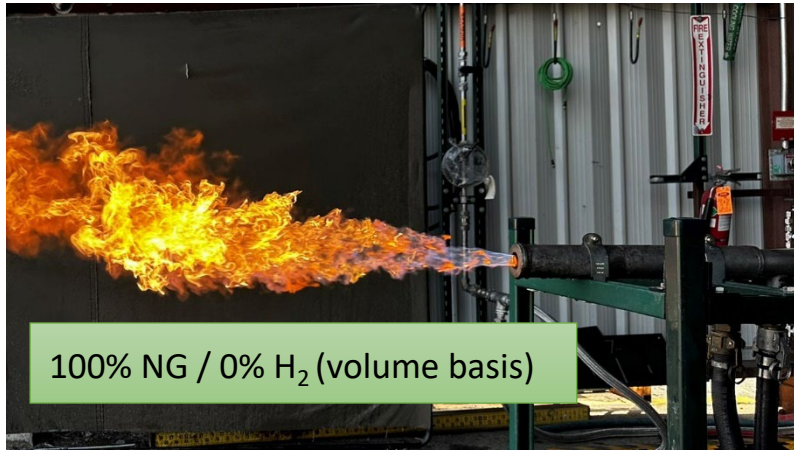
Hydrogen Combustion Trials Since 2018 – 1(4)

Oxyfuel Firing



Hydrogen Combustion Trials Since 2018 – 2(4)

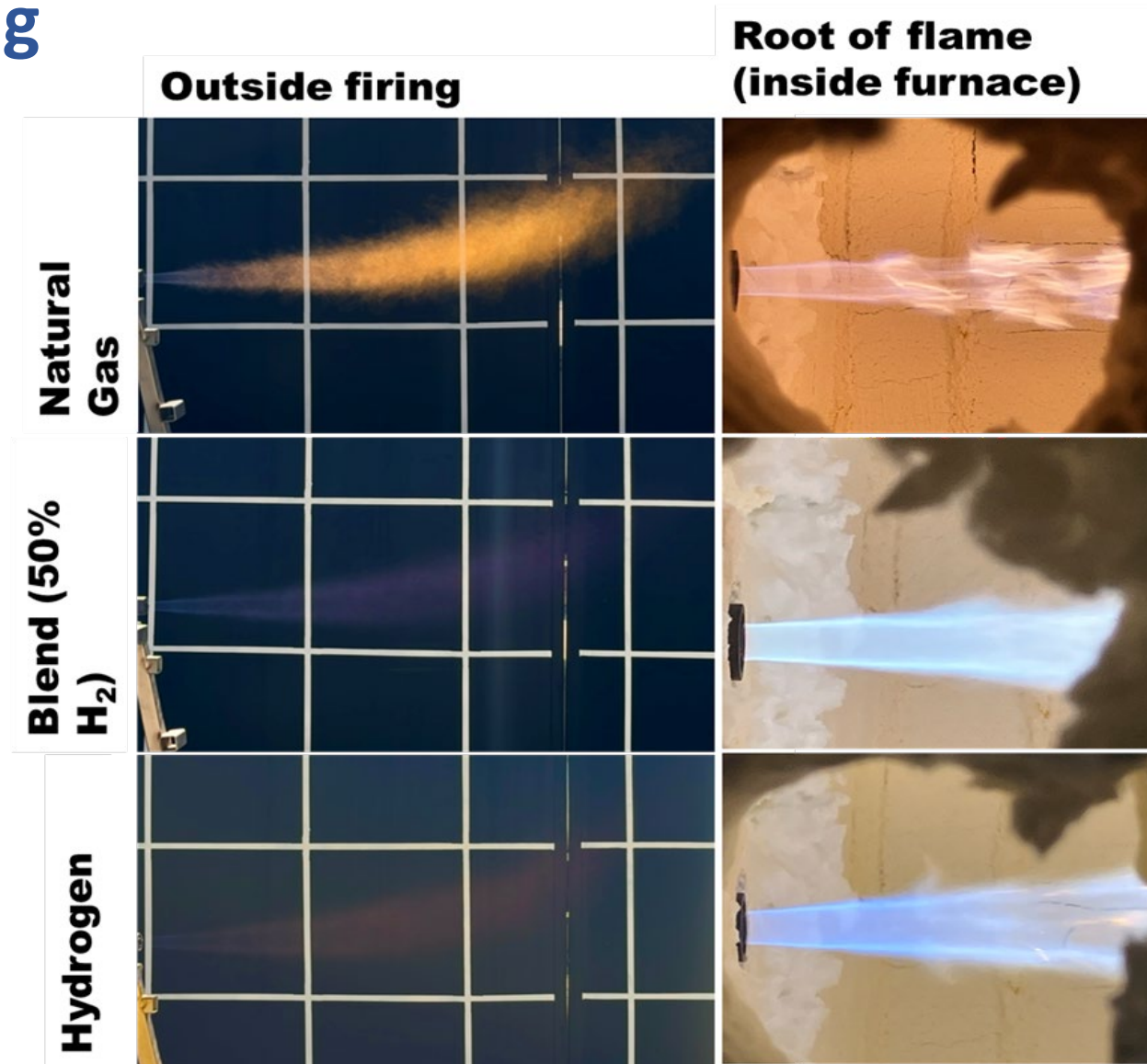
Oxyfuel Firing - Flame Influence of Hydrogen Enrichment of Natural Gas



Hydrogen Combustion Trials Since 2018 – 3(4)

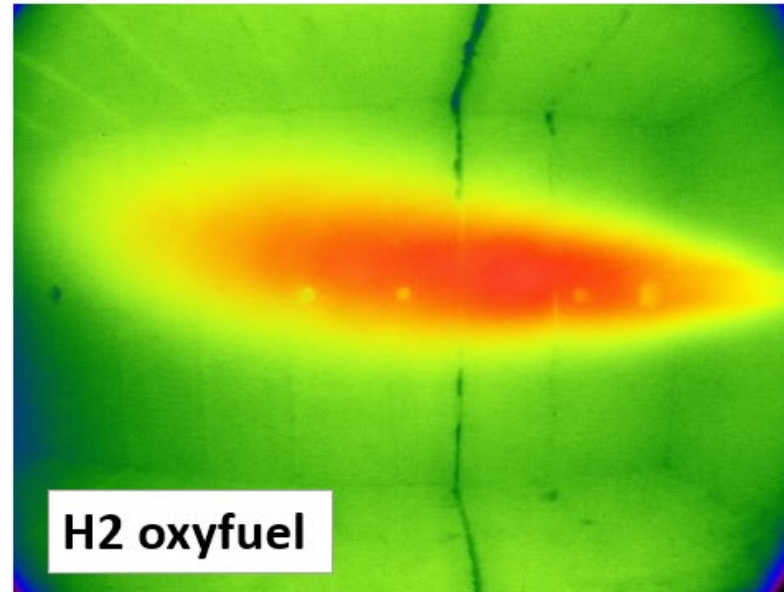
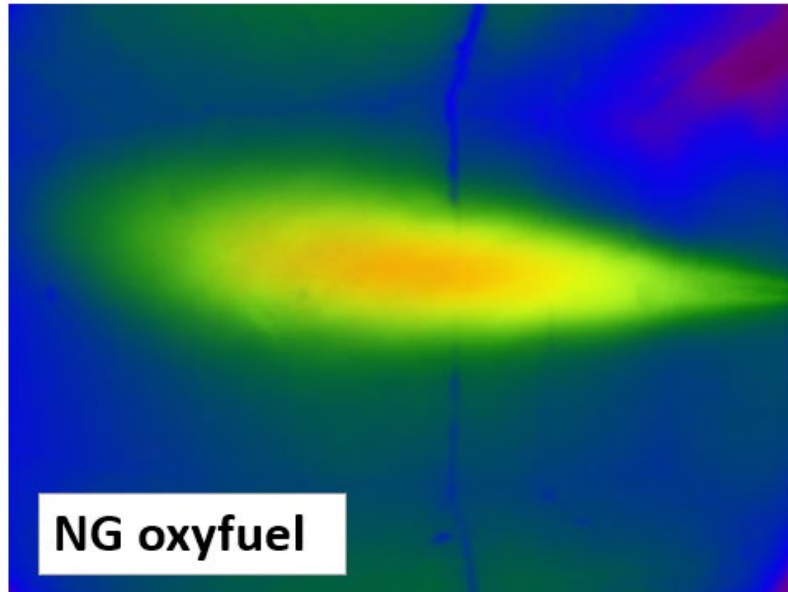


Oxyfuel Firing



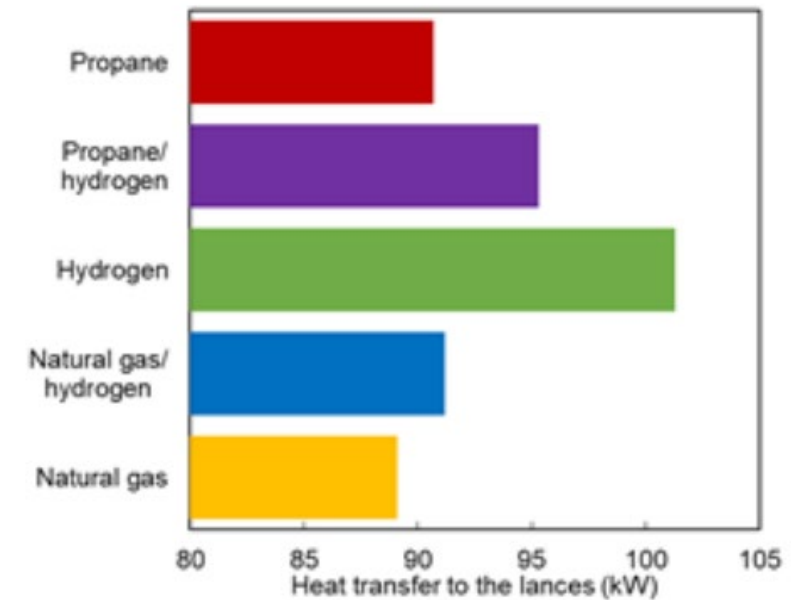
Hydrogen Combustion Trials Since 2018 – 4(4)

Oxyfuel Firing



Thermal camera images from 200 kW oxyfuel burner firing inside a furnace

Results from pilot-scale tests of heat transfer using various fuels



Oxyfuel Combustion with Hydrogen



- **Linde has implemented 100% oxygen + 100% hydrogen combustion in various applications for many years, e.g., more than 50 installations for polishing in the Glass industry.**
- **Blending in hydrogen up to 100% works very well from a combustion point-of-view.**
- **Flameless Oxyfuel combustion with 100% hydrogen can operate without increasing the NO_x emissions, i.e., not resulting in any negative trade-off between lowering CO₂ and lowering NO_x emissions; both can be reduced simultaneously.**
- **Applying oxyfuel combustion has a larger impact on reducing carbon footprint than blending in 50% hydrogen in natural gas at air-fuel combustion. A 50/50 blend would decrease the carbon footprint by 20-25%, i.e., same or less than what would be achieved with a conversion into oxyfuel without using any hydrogen.**

CoJet[®] Coherent Jet Technology

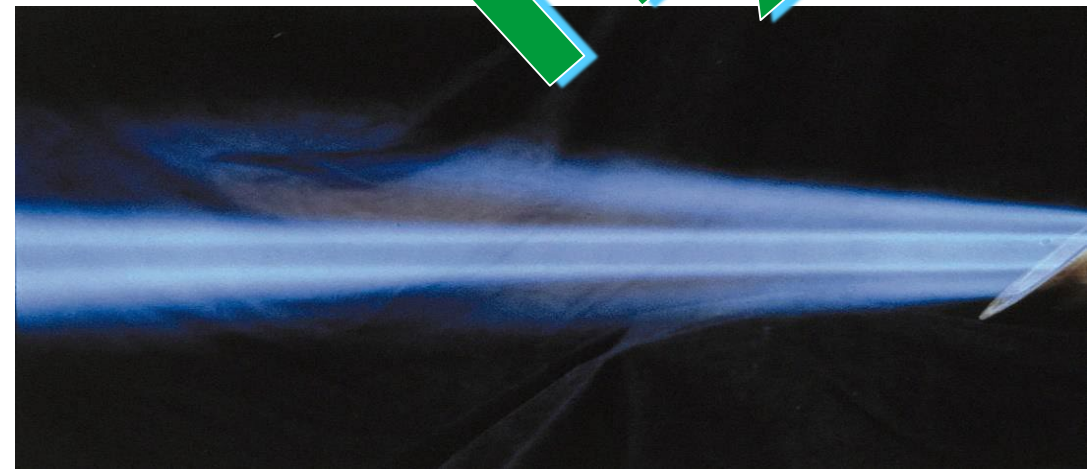


The use of CoJet, Developed by Linde, has Revolutionized Electric Arc Furnace Steelmaking Since 1996.

To Date: 175+ Successful Installations Worldwide

Multiple Tests Carried Out with Hydrogen as a Fuel

It has been Demonstrated that Hydrogen is the Best Fuel for CoJet - Hydrogen Produces the Longest Jets!



Gas Cutting with 100% Oxygen-Hydrogen at Continuous Casting of Steel



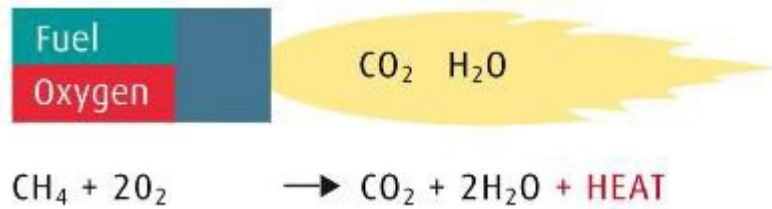
- Oxygen-hydrogen torches to cut at continuous casters
- First tested at Linde's Tech Center in Stockholm, Sweden
- Multiple on-site trials at steelmakers have shown:
 - Half the burner power required
 - Double the cutting speed!



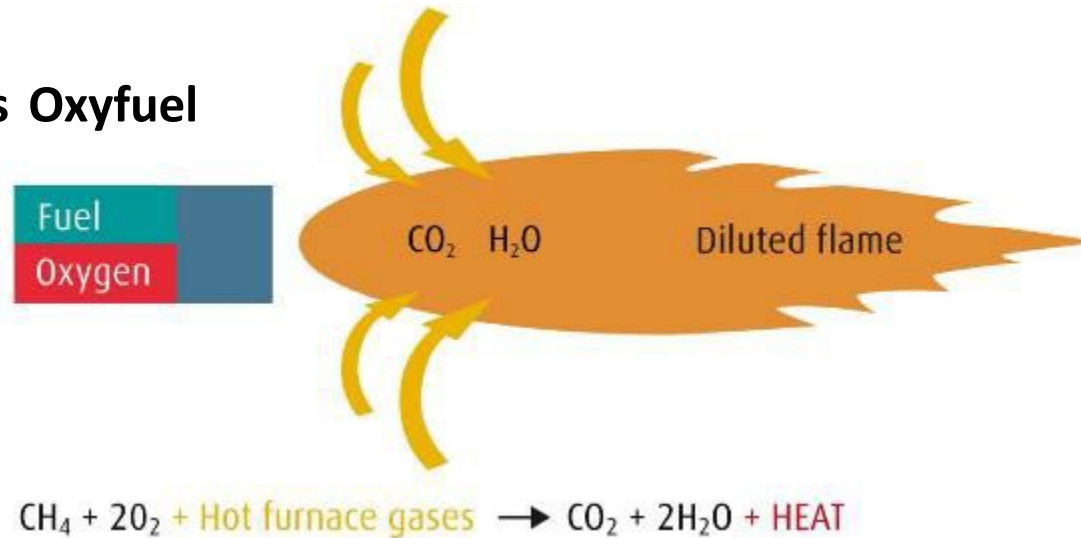
Conventional Oxyfuel and Flameless Oxyfuel



Conventional Oxyfuel



Flameless Oxyfuel



OXYGON® Flameless Oxyfuel Ladle Preheating

200+ Installations; 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 CO₂ 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_x emissions
- Can operate with H₂ or mixtures of H₂ and other fuels; 100% H₂ can give 100% reduction of CO₂ emissions

OXYGON® Flameless Oxyfuel Tundish Preheating

The World's First Two Installations Now in Operation



- 30-tonne tundishes at Siam Yamato Steel in Thailand
- 4/5 x 0.3 MW Flameless Oxyfuel
- >60% lower fuel consumption and CO₂ emissions
- Possibility to reach very high pre-heating temperatures
- Ultra low NO_x emissions
- Can operate with H₂ or mixtures of H₂ and other fuels; 100% H₂ can give 100% reduction of CO₂ emissions



REBOX® Oxyfuel Solutions in Steel Reheating and Annealing

190 Installations at 40+ Steel Mills



REBOX Oxyfuel Installations:

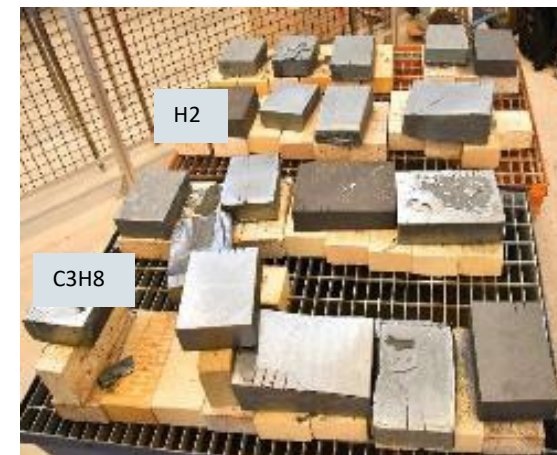
- In total 190 to date
- Thereof 30 as REBOX HLL (hybrid solution)
- 33 in stainless steel production
- 12 in new furnaces
- 27 in Walking Beam Furnaces



Steel Reheating with Hydrogen Oxyfuel Lab Scale Trials in October 2019



- REBOX[®] Flameless Oxyfuel was used to reheat 10 kg steel samples from four steel producers (Alleima, Outokumpu, Ovako, SSAB)
- The samples were tested with propane and hydrogen as fuels, using the same burner without any changes or modifications. Identical heating curves were used.
- The almost 100% water vapor content of hydrogen oxyfuel had no measurable impact on key process parameters; scaling, de-scaling, decarburization, hydrogen embrittlement, heating capacity, temperature uniformity and NO_x formation
- The steel product quality was unchanged



Steel Reheating with Hydrogen Oxyfuel Full Scale Test in March 2020

OVAKO



- In March 2020, Ovako and Linde performed a full-scale demonstration using 100% REBOX Flameless Hydrogen Oxyfuel firing in a soaking pit furnace at Ovako's mill in Hofors, Sweden
- The existing REBOX Flameless Oxyfuel combustion system was upgraded to use both hydrogen and LPG as fuel
- At the full-scale test, 24 ball-bearing steel ingots (100 tonnes combined) were charged into four pits. One using hydrogen as fuel while the three others operated normally with LPG
- *A world 1st*



Steel Reheating with Hydrogen Oxyfuel Permanent Industrial Operation Since 2024

OVAKO

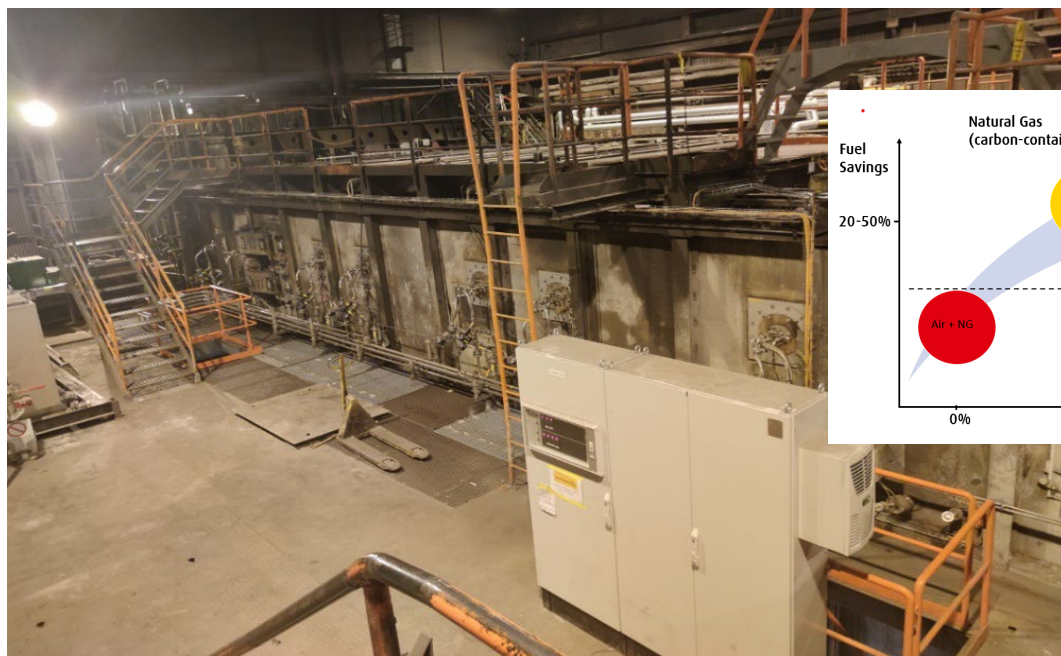


- A 20 MW alkaline electrolyzer onsite was commissioned at the beginning of 2024, producing up to 4,000 Nm³/h of H₂ from 100% renewable energy. The oxygen is also supplied using renewable energy.
- All 48 soaking pits had been converted to 100% REBOX Hyox. The world's first industrial-scale 100% hydrogen fired oxyfuel combustion.
- It has been operating successfully since then, with no changes in heating power, heating profile, rolling forces, dimensions, scale losses or temperature uniformity.
- To date 500,000 tonnes of alloyed steel have been heated successfully.



Conversion of Continuous Steel Reheating Furnaces from Air-fuel to 100% Full Flameless Oxyfuel

2023 Conversion at Imatra Steel Mill, Finland

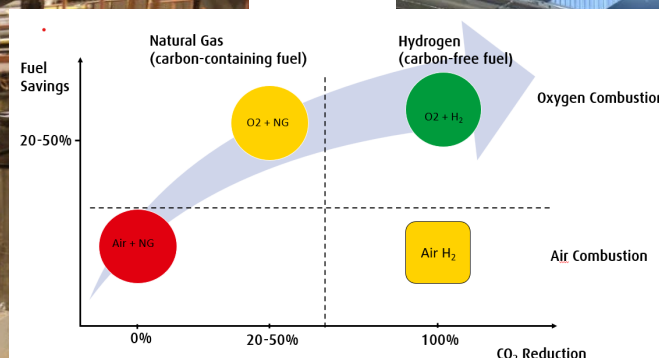


>25% Less Fuel Consumption

2024 Conversion at Boxholm Steel Mill, Sweden



>50% Less Fuel Consumption



REBOX[®]

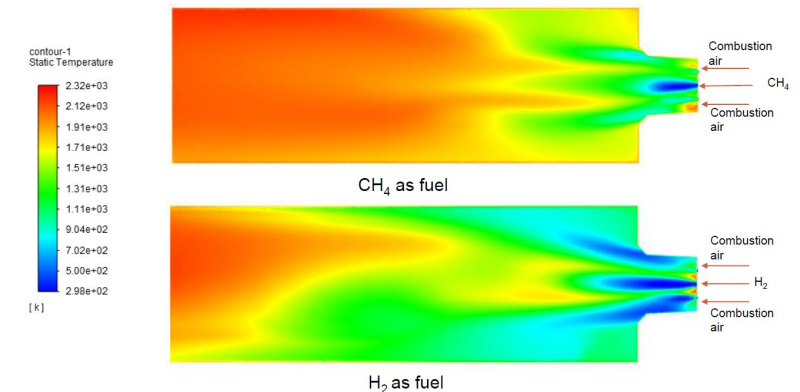
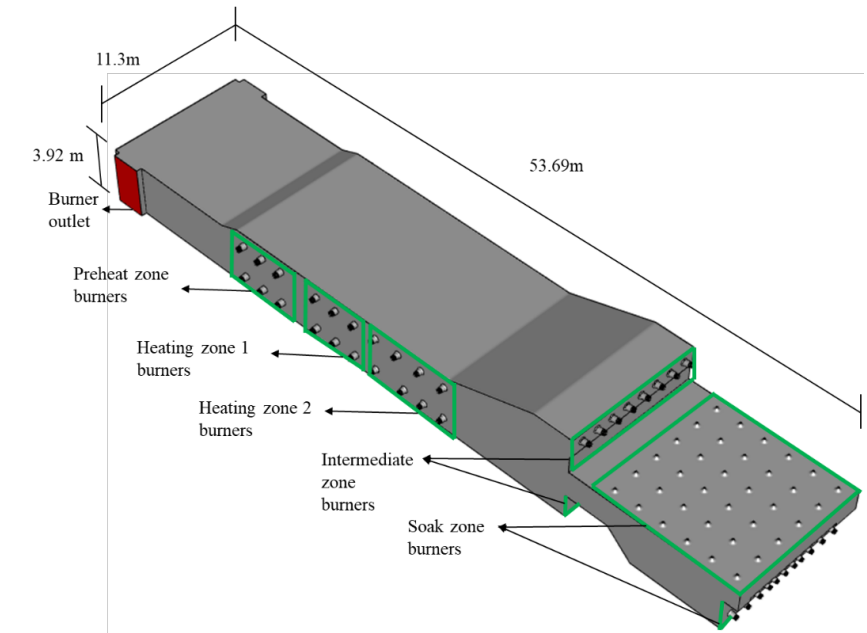
Hydrogen as a Fuel in a Walking Beam Furnace



GERDAU



First-of-its-kind, industry-scale demonstration of hydrogen fired continuous walking beam reheating furnace to take place at a Gerdaul steel mill in the USA



Use of Oxyfuel and Hydrogen in a Large Reheat Furnace

Air-fuel and Oxyfuel with 0%, 50%, 100% Hydrogen



Basic Assumptions:

- Furnace at 100 MW air-fuel power
- Operating at 70 MW with Oxyfuel (-30%)
- 100% renewable power with zero carbon footprint
- Hydrogen supplied from electrolyzer plant
- 1 Nm³ NG = 10 kWh => 2 kg CO₂
- 1 Nm³ H₂ = 3 kWh => 0 kg CO₂
- 1 Nm³ O₂ requires 0.4 kWh
- 1 Nm³ H₂ requires 4.5 kWh

	MW	NG (Nm ³ /h)	H ₂ (Nm ³ /h)	O ₂ MW	H ₂ MW	Total MW	CO ₂ (t/h)	Diff. CO ₂
Air-fuel 0/100	100	10,000	0	0	0	0	20	Base
Air-fuel 50/50	100	7,700	7,700	0	35	35	15.4	-23%
Air-fuel 0/100	100	0	33,350	0	150	150	0	-100%
Oxyfuel 0/100	70	7,000	0	6	0	6	14	-30%
Oxyfuel 50/50	70	5,400	5,400	6	24	30	10.8	-46%
Oxyfuel 0/100	70	0	23,350	6	105	111	0	-100%

Estimated Use of Hydrogen in the Steel Industry by 2040



DRI Production	2.6 Mt	}	Reducing Gas (70%)
Blast Furnaces	0.4 Mt		
EAF, Preheating, Cutting	0.2 Mt	}	Fuel (30%)
Reheating	1.0 Mt		
Total	4.2 Mt		

"Catch-H2"



Expectations on substantially lower hydrogen prices in the future makes potential offtakers postpone signing agreements necessary for investments required to scale-up of supply needed to greatly decrease the cost of producing hydrogen.

Why Low Carbon Hydrogen (LCH)?

Transition NG → Blue Hydrogen → Green Hydrogen

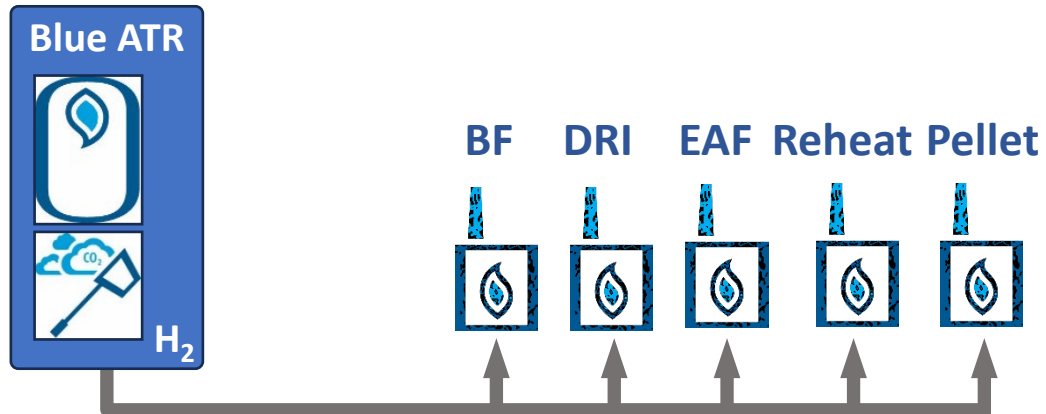


Compared to hydrogen from electrolyzer:

- **LCH is cheaper** than Green H₂ in many geographies.
- Available at **large scale** (220,000 t/y; equivalent of 1 GW electrolyzer plant => 2+ Mt/y of DRI)
- Technology is **mature** and ready for commercial implementation.

Compare to steel mill CO₂ capture:

- Multi-point CO₂ capture is expensive. LCH can be sent to **multiple locations in the steel mill to decarbonize the whole plant.**



Natural gas → ATR + CCS → Blue Hydrogen

Carbon footprint can be at 1-2 kg CO₂ per kg H₂

Successful Full-Scale Implementation of Hydrogen as a Fuel

Summary



- In the steel industry, hydrogen can be used as a reducing gas and as a fuel.
- When used as a reducing gas, typical hydrogen supply would be at 50,000 – 250,000 Nm³/h whilst when used as a fuel it is rather at 5,000 – 50,000 Nm³/h.
- Hydrogen as a fuel has been proven to work well without any negative impact on oxyfuel combustion in EAFs, ladle preheating, cutting, and reheating operations.
- Applying oxyfuel combustion has larger impact on reducing carbon footprint than blending in 50% hydrogen in natural gas at air-fuel combustion.
- For reheating, 500,000 tonnes have already been heated in a full-scale permanent installation in batch furnaces at Ovako in Sweden using 100% hydrogen + 100% oxygen.
- Full-scale tests in reheating have taken place using up to 3 MW in continuous furnaces.
- Large scale tests and installations with hydrogen in continuous furnaces are under way.
- All Linde Flameless Oxyfuel installations for ladle preheating, tundish preheating, and steel reheating are made ready for use of hydrogen as a fuel.



Thank you for your attention

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www.linde.com

Making our world more productive