Decarbonisation and Use of Hydrogen in Reheat Furnaces

Dr. Joachim von Schéele
Director Global Commercialization

Making our world more productive

Linde - Technologies and Gases Supporting Steelmaking

World's Largest Industrial Gases Company

- Sales at €25 billion
- Market Capitalisation at €130 billion
- Activities in 100+ Countries
- 75,000+ Employees
- 6,500+ Patents

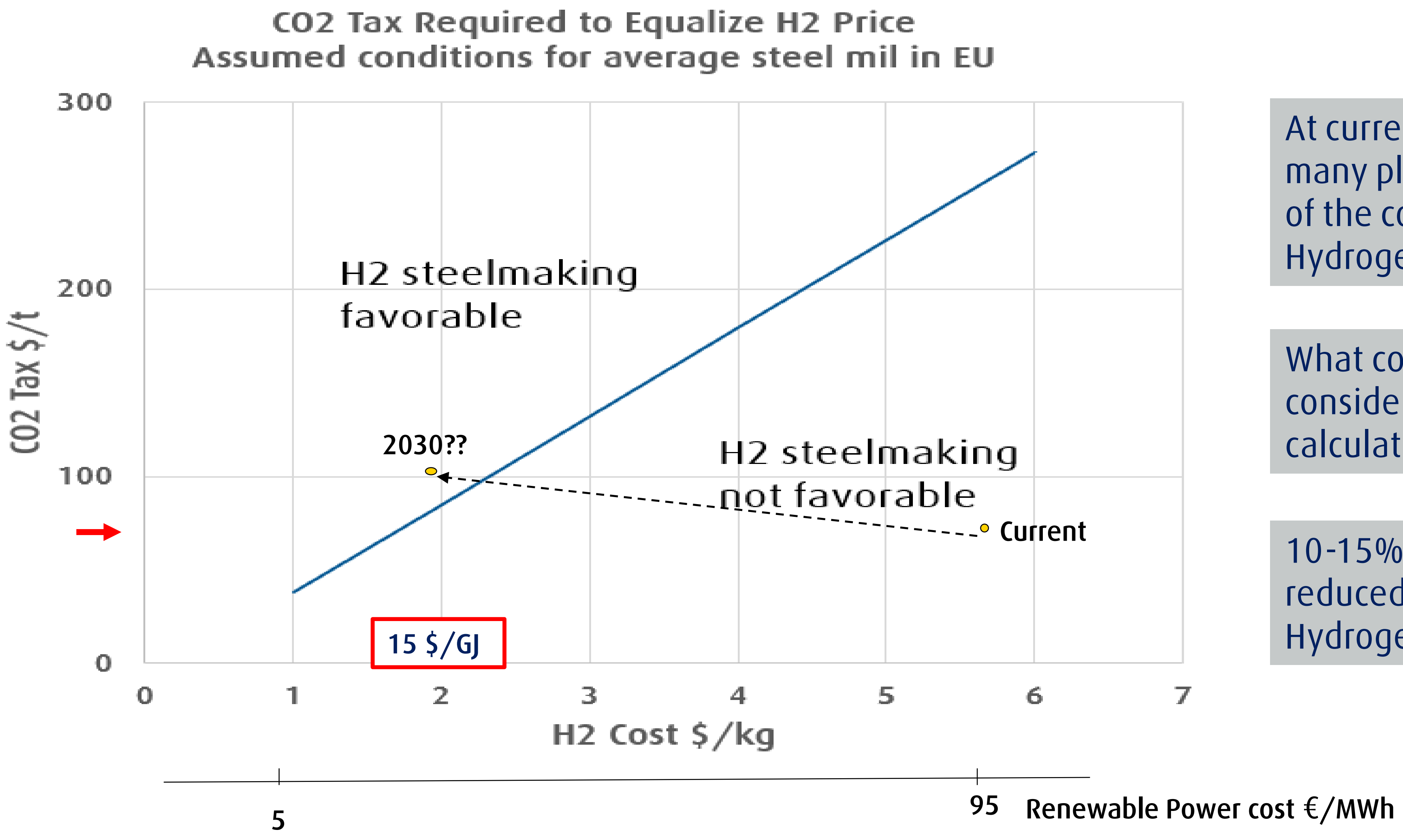
World-leading Supplier of Hydrogen

- Sales at €2 billion/year
- Active Across the Whole Value-chain
- Part-owner of ITM Power
- Building world's largest PEM Electrolyser
- Tripling Clean Hydrogen Capacity by 2028

Provider of Leading Steelmaking Technologies

- AOD – 75% of all stainless steel production today
- CoJet® – 170+ installations in Electric Arc Furnaces
- REBOX® – 180+ installations in Reheat Furnaces

The Decarbonisation Challenge
The Cost of Hydrogen

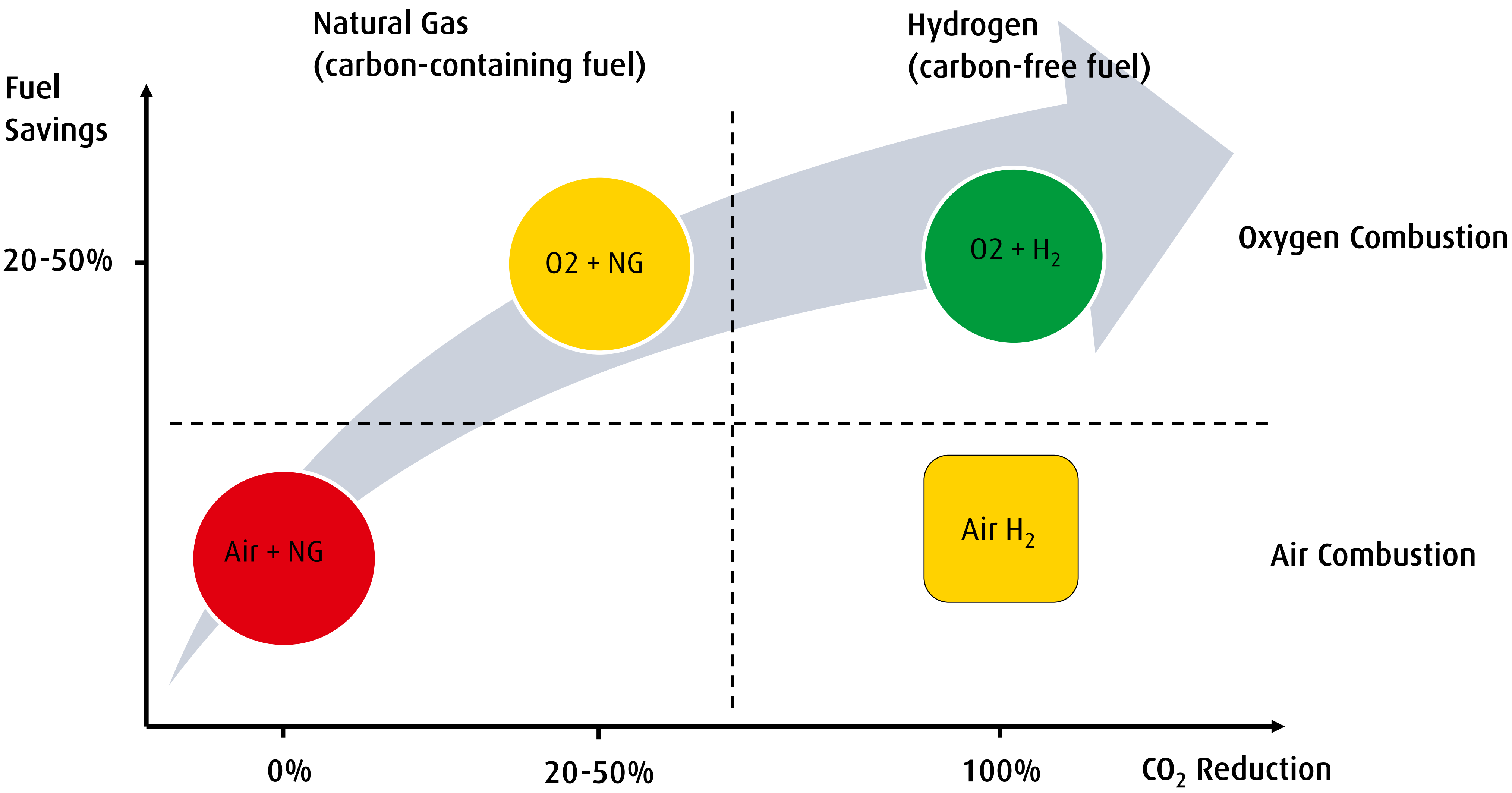


At current electricity prices at many places in Europe, 60-70% of the cost to produce Green Hydrogen relate to **Electricity**

What cost of CO_2 emissions to consider for investment calculations? 80? 100? 150?

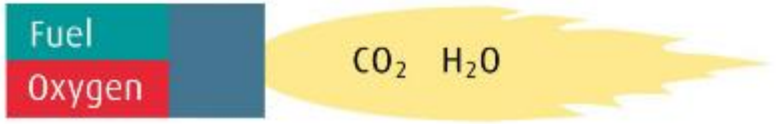
10-15% of CO_2 emissions can be reduced without use of Hydrogen and any cost penalty!

Route to Decarbonize Industrial Heating Operations

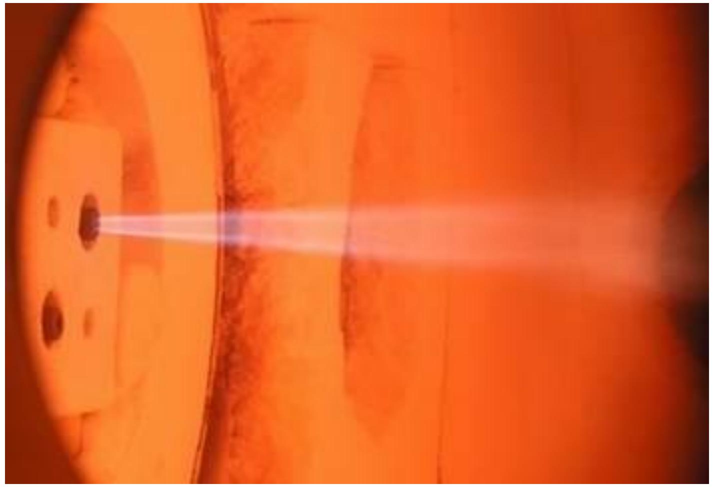


Conventional Oxyfuel and Flameless Oxyfuel

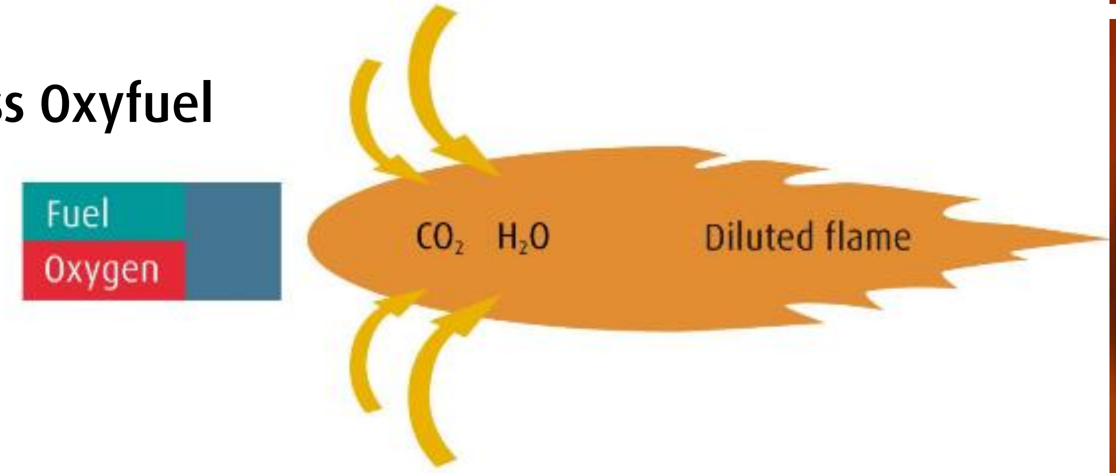
Conventional Oxyfuel



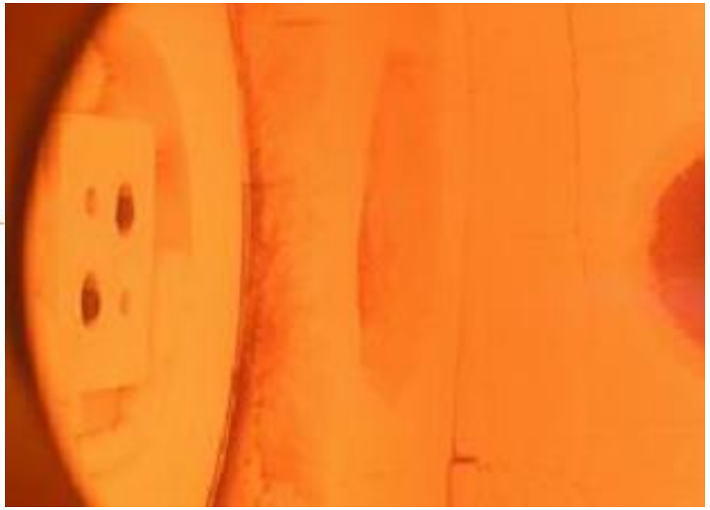
$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$ + HEAT



Flameless Oxyfuel

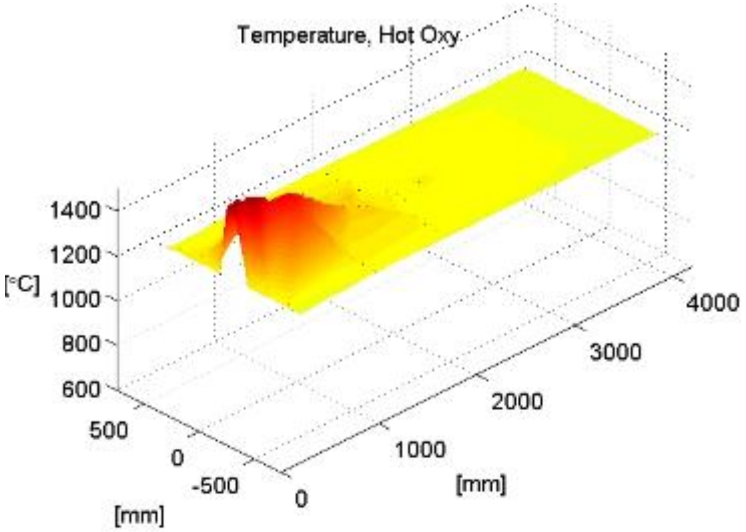


$CH_4 + 2O_2$ + Hot furnace gases $\rightarrow CO_2 + 2H_2O$ + HEAT

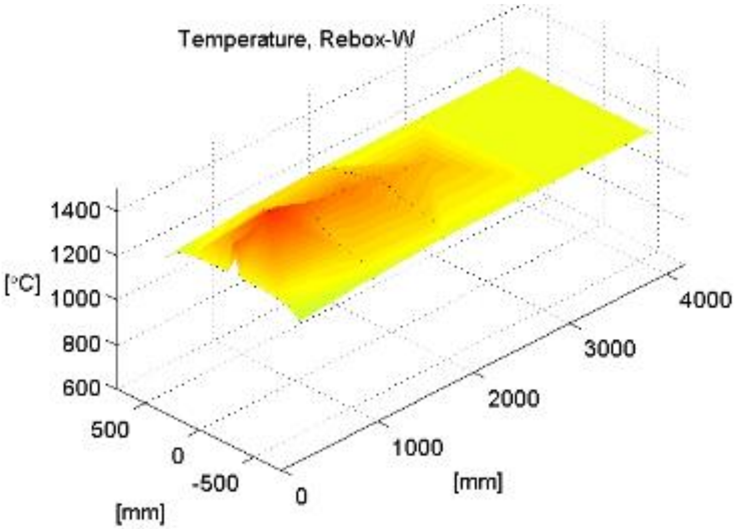


Flame Temperature Profiles of Conventional Oxyfuel and Flameless Oxyfuel

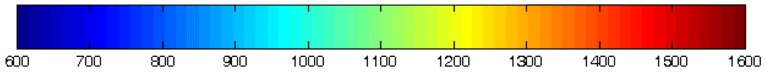
Data from evaluation by Royal Institute of Technology (KTH), Sweden; furnace at 1200ºC

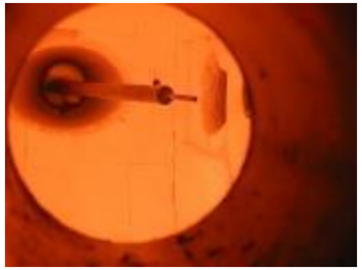


Conventional Oxyfuel



Flameless Oxyfuel





Same Peak Temp as Air-fuel, but Better Uniformity

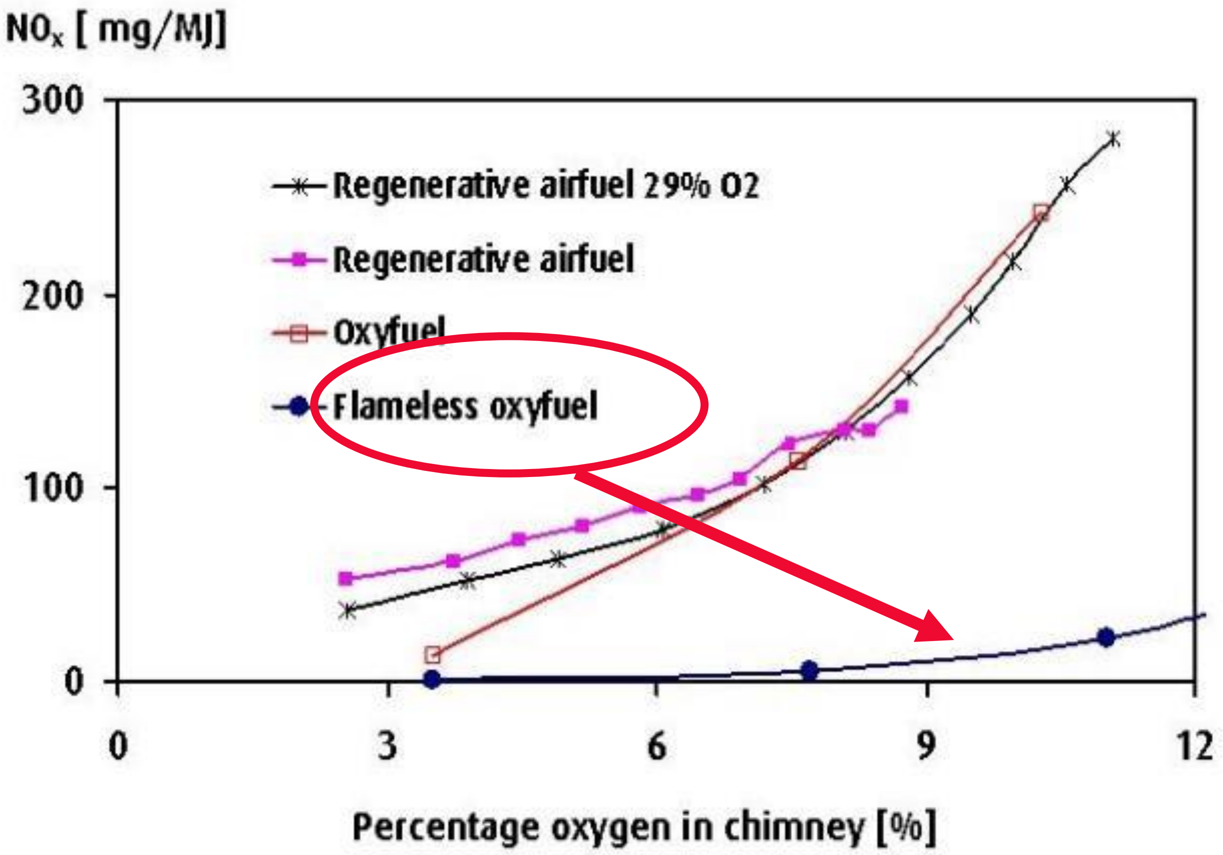
No generation of Thermal NOx

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

Flameless Oxyfuel
Lower NOx Emissions

Measured NO_X, data from evaluation by Royal Institute of Technology (KTH), Sweden

With Flameless Oxyfuel NOx levels much less sensitive to in-leakage of air

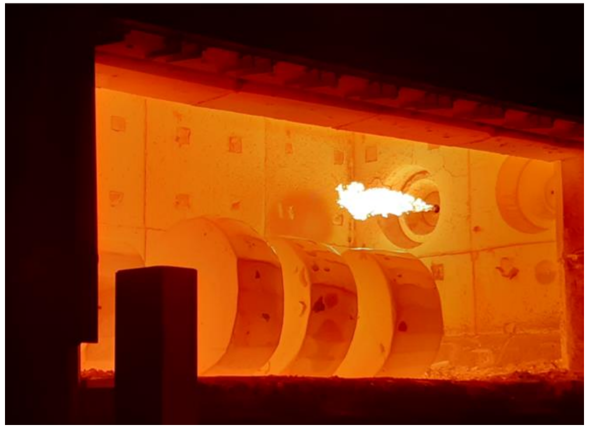


Installations of REBOX Oxyfuel Solutions in Steel Reheating have Resulted in:

- 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%

180+ REBOX® Oxyfuel Installations at 40+ Steel Mills Across the World
Examples of Sites with Installations in Reheating and Annealing

Amsteel, Bukit Raja (MY)
ArcelorMittal, Galati (RO)
ArcelorMittal, Indiana Harbor (US)
ArcelorMittal, Shelby (US)
Ascométal, Les Dunes (FR)
Ascométal, Fos-sur-Mer (FR)
Bei Ye, Beijing (CN)
Celsa, Mo i Rana (NO)
Dongbei Special Steel, Dalian (CN)
Electrosteel, Kharda (IN)
Ellwood City Forge, Ellwood City (US)
Evraz Steel, Claymont (US)
Gerdau Cosigua, Rio de Janerio (BR)
Hospet Steel, Hospet (IN)
Jindal SAW, Nashik (IN)
Jindal Stainless, Hisar (IN)
Kalyani Carpenter Special Steels, Pune (IN)
Mahindra Sanyo Special Steel, Khopoli (IN)
Malaysia Steel Works, Bukit Raja (MY)
Malaysia Steel Works, Petaling Jaya (MY)
Marienhuette, Graz (AT)
Masteel, Ma'anshan (CN)
Michigan Seamless Tube, South Lyon (US)
North American Forgemasters, New Castle (US)
Nucor, Auburn (US)
Outokumpu, Avesta (SE)
Outokumpu, Degerfors (SE)
Outokumpu, Nyby (SE)
Outokumpu, Tornio (FI)
Ovako, Hofors (SE)
Ovako, Smedjebacken (SE)
POSCO, Pohang (KR)
Sandvik Materials Technology (SE)
Scana Steel, Björneborg (SE)
Siam Yamato Steel, Rayong (TH)
SSAB, Borlänge (SE)
ThyssenKrupp Steel, Bruckhausen (DE)
ThyssenKrupp Steel, Finnentrop (DE)
TMK Ipsco, Koppel (US)
Vedik Ispat, Hindupur (IN)
Yongxing Stainless Steel, Huzhou (CN)
Zhongxing Energy, Haimen (CN)



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.

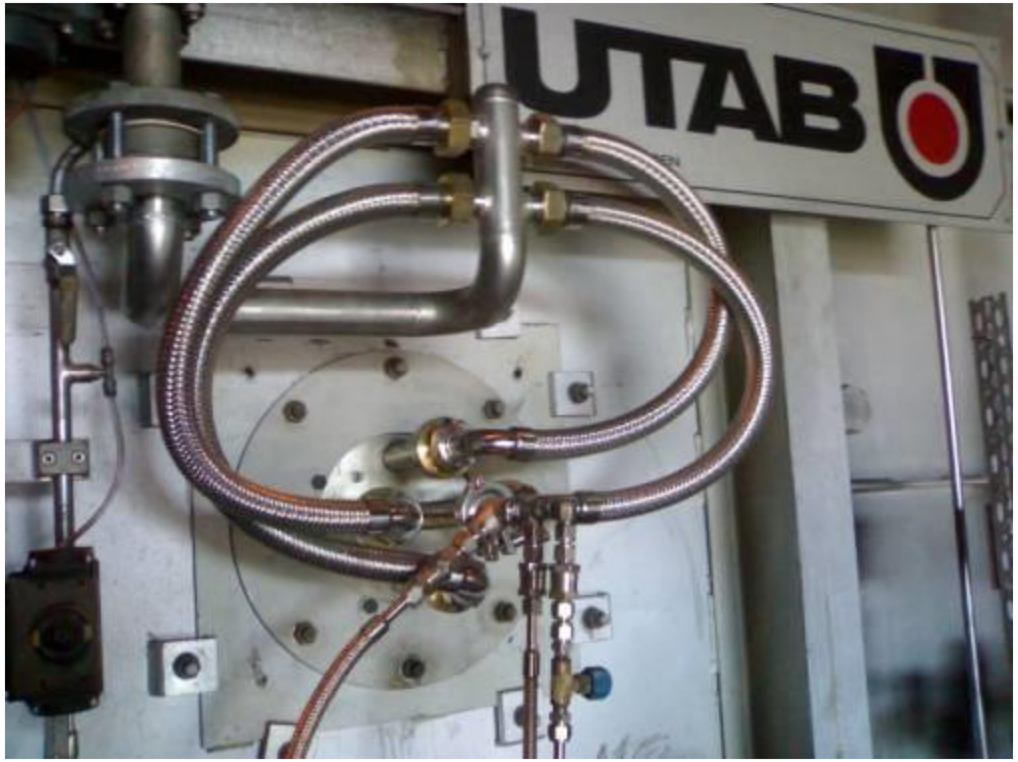
30% Capacity Increase

30% Fuel Savings

REBOX® Installations at Outokumpu

Catenary furnace at Outokumpu, Avesta (SE)
Conversion into 100% Flameless Oxyfuel operation

40 MW Flameless Oxyfuel; Capacity 150 tph, 40% fuel saving



REBOX® DST – Roller Hearth with 100% Flameless Oxyfuel

Yongxing Special Stainless Steel, Huzhou (CN)

The World's Most Energy-efficient Annealing of Stainless Wire Rod!

Total natural gas consumption including idling time is below 7 Nm^3/t, which equals 80% fuel savings compared to batch annealing.

REBOX® Installations at Sandvik

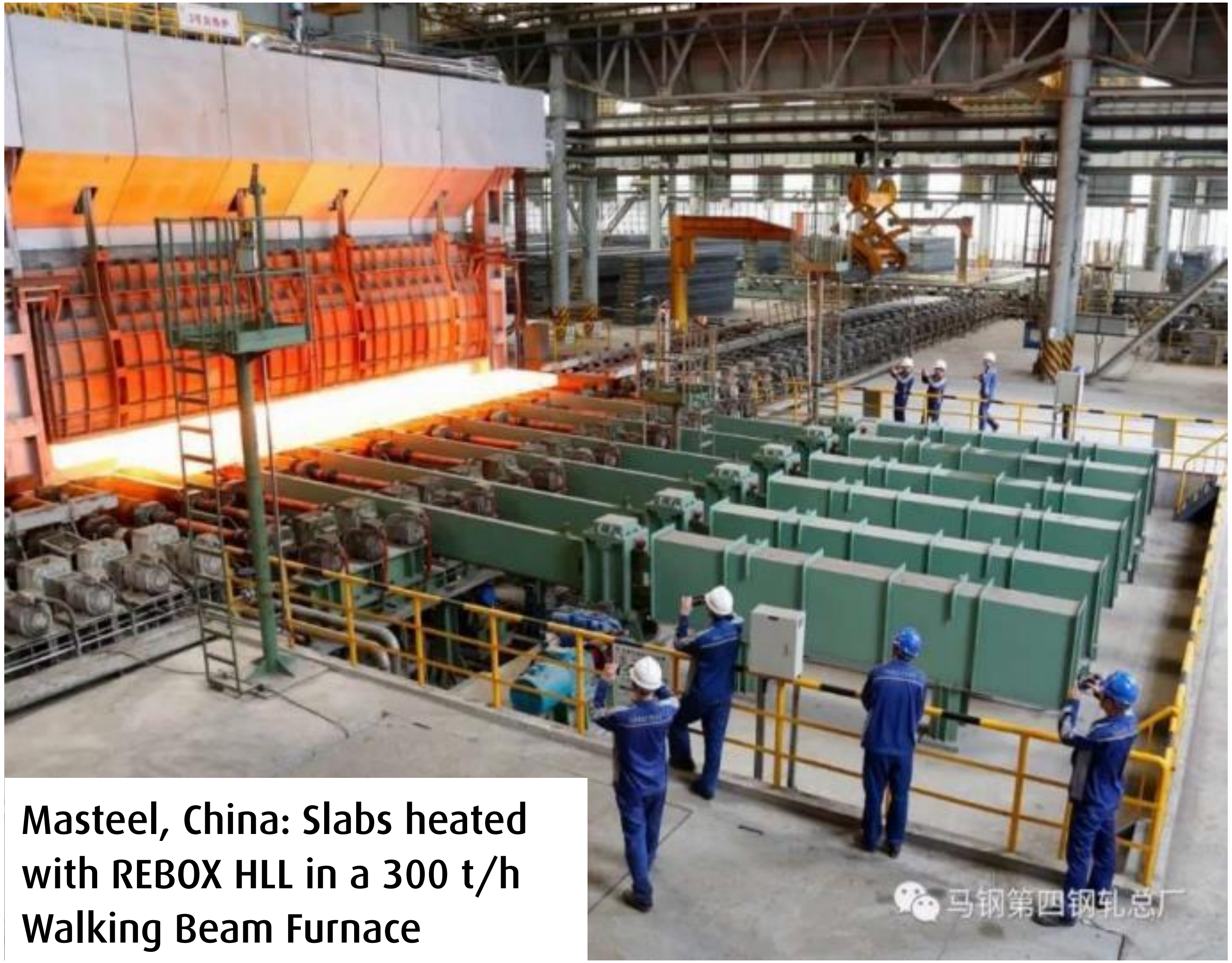
REBOX® HLL

No full conversion, but more capacity and less fuel consumption

- Add-on solution to existing air-fuel burners
- Minimum installation down time
- Great flexibility, can be turned on and off with a response time of 1 minute
- Optimized in response to fluctuating fuel cost and productivity requirement
- Beneficial use of LCV fuel
- Capacity increase at 15-20%
- Fuel and CO_2 saving at 15-30%
- Improve temperature uniformity
- Reduced scale losses

REBOX HLL at Outokumpu, Tornio (Finland)

REBOX® HLL



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

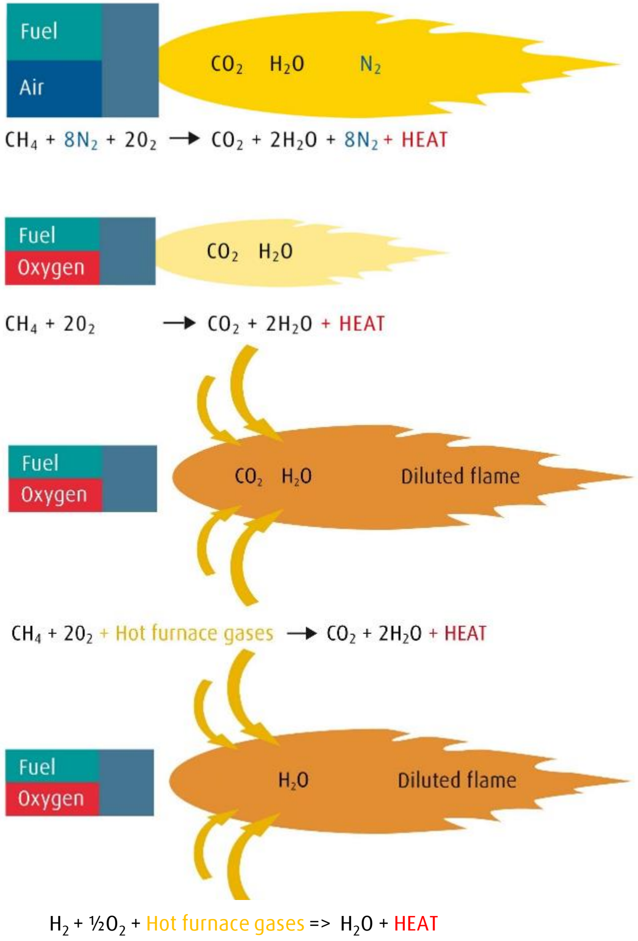
Add-on system, typically put in the pre-heating and/or heating zones

10-30% lower fuel consumption and CO_2 emissions, lower NOx emissions

2021 REBOX HLL – Commissioned and New Contracts:

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

Comparison of CO_2 Emissions of Various Combustion Technologies



Air-fuel combustion (methane as fuel)
400 kWh/t => 80 kg CO_2/ton

Conventional Oxyfuel (with methane as fuel)
290 kWh/ton => 58 kg CO_2/ton

Flameless Oxyfuel (with methane as fuel)
270 kWh/ton => 54 kg CO_2/ton

Flameless Oxyfuel (with hydrogen as fuel)
270 kWh/ton => 0 kg CO_2/ton

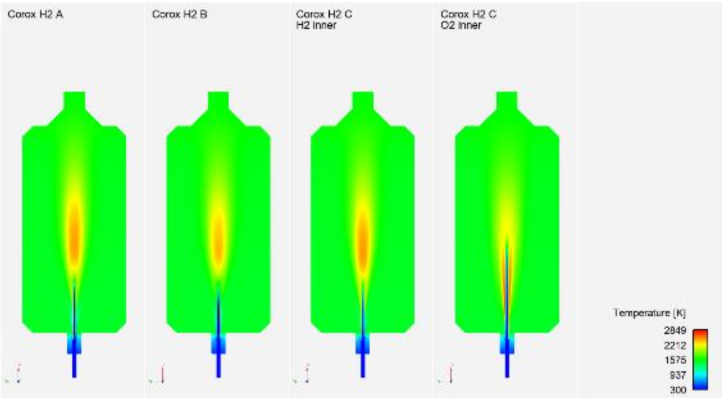
Flameless Hydrogen Oxyfuel facilitates high temperature flue gas condensation to further improve energy efficiency

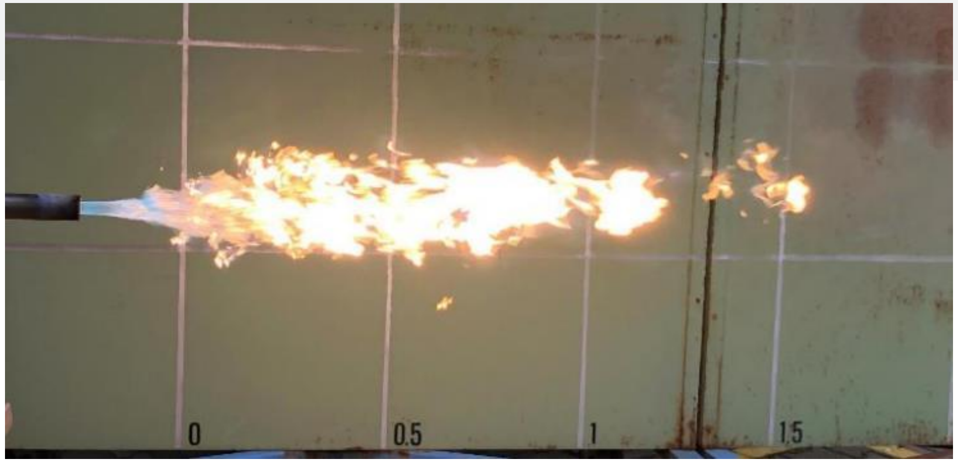
Comparison of Various Fuel Gases

*Different sources provide slightly different values and use different reference points, e.g. 0°C, 15°C or 21.1°C. These are **selected** (and sometimes) **average** values for **comparative purposes** only!*	Hydrogen (H_2)	Methane	Propane	n-Butane	Carbon Monoxide
(Some) Hazards	*combustible*	*greenhouse*	*greenhouse*	*greenhouse*	*poisonous*
Molecular Weight (g/mol)	2,0158	16,04	44,1	58,12	28,01
Density (kg/Nm^3)	0,0899	0,7175	2,0098	2,709	1,25
Specific Gravity (air = 1)	0,0695	0,555	1,554	2,095	0,967
Speed of Sound (m/s)	1290	466	250		336
Specific Heat Capacity cp (kJ/(**kg**.°C))	14,3	2,232	1,696	1,734	1,041
Specific Heat Capacity cp kJ/(**Nm3**.°C)	1,286	1,601	3,409	4,697	1,301
Dynamic Viscosity (x 10^{-6} Ns/m^2))	8,92	11,2	8,3	7,51	17,7
Auto Ignition Temperature in Air (°C)	572	632	493	405	608
Auto Ignition Temperature in Oxygen (°C)	560	556	468	283	588
Theoretical Volume Oxygen Required for Combustion (Nm^3 O_2/Nm^3 fuel)	0,5	2	5	6,5	0,5
Theoretical Volume Air Required for Combustion (Nm^3 air/Nm^3 fuel)	2,4	9,6	23,9	31,1	2,4
Adiabatic Flame Temperature with Air (°C)	2125	1942	2007	2020	2115
Adiabatic Flame Temperature with Oxygen (°C)	2894	2710	2744	2751	2625
Lower Heating Value (kJ/Nm^3)	10758	35874	93680	123738	11570
Lower Heating Value (kWh/Nm^3)	2,99	9,97	26,02	34,37	3,21
Lower Heating Value (kWh/kg)	33,24	13,89	12,95	12,69	2,57
Specific Oxygen Demand (Nm^3 O_2 / kWh)	0,17	0,20	0,19	0,19	0,16
Flue Gas Volume for ***Oxyfuel Combustion*** (Nm3/kWh)	0,336	0,300	0,267	0,263	
Upper Flammability Limit in Air (vol%)	4	5	2,1	1,8	12
Lower Flammability Limit in Air (vol%)	74,2	15	13,8	8,4	75
Upper Flammability Limit in Oxygen (vol%)	4,7	5	2,3	1,8	16
Lower Flammability Limit in Oxygen (vol%)	93,3	61	55	49	94
Detonability Limit in Air (vol%)	18 - 59	6,3 - 13,5			
Flame Propagation Velocity in Air (m/s)	2,83	0,45	0,46	0,4	0,52
Flame Propagation Velocity in Oxygen (m/s)	11,7	4,5	3,72	3,55	
Minimum Ignition Energy in Air (µJ)	20	290			
Theoretical Explosive Energy (kg TNT/m^3 gas)	2,02	7,03			
Diffusion Coefficient in Air (cm^2/s)	0,61	0,16			

Linde Technology Centre Munich
Initial Hydrogen Oxyfuel Tests, Spring 2019

- ➔ Comparison between LPG and H_2 using the same (NG) burner.
- ➔ CFD modelling started and a series of burners for glass tanks built and ready to be tested.





<u>Photos, clockwise from top left:</u>

250 kW Propane Oxyfuel (LPG 16 & 02 45 m/s)
- NG design 42 & 45 m/s

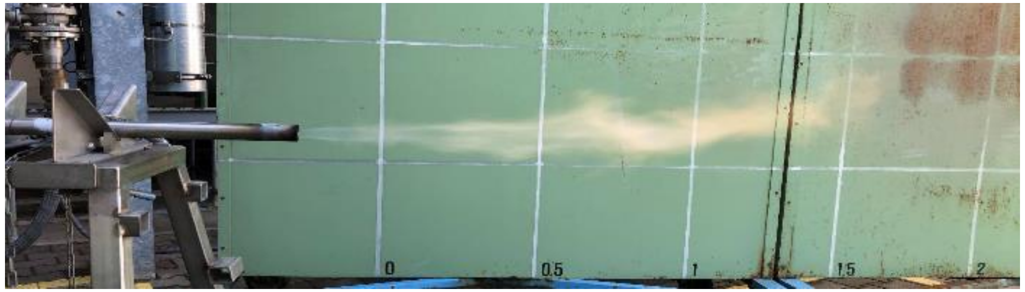
Hydrogen flame with ambient air during fuel change over - danger!

250 kW Hydrogen Oxyfuel (150 & 38 m/s) - visible flame slightly shorter

Linde Technology Centre Munich
500 kW Hydrogen Oxygen Burner Control System

Linde

➔ EN 746-2 compliant control



Linde Technology Centre Munich
Hydrogen Trials

Open air firing of 300 kW COROX burner for Glass melting

High concentration of Water Vapour creates infrared radiation

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

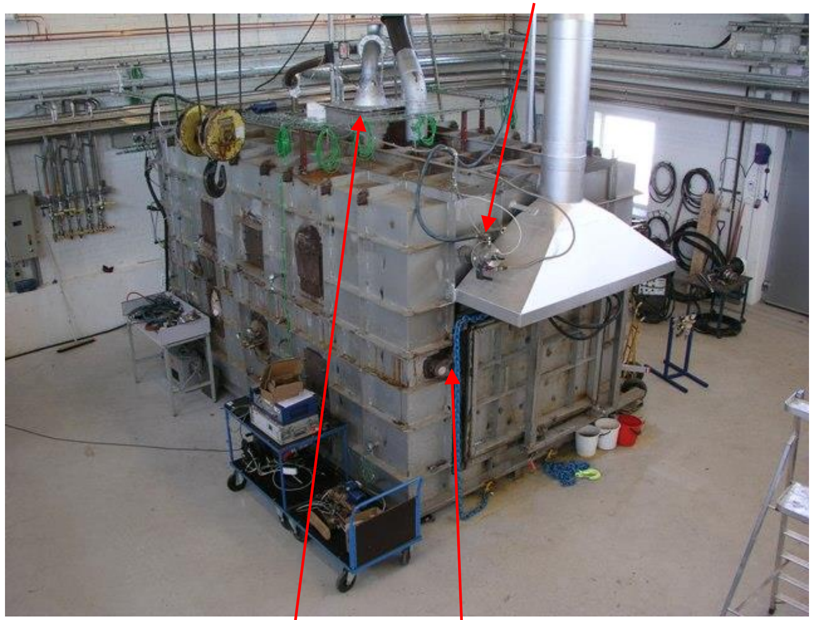
Natural Gas fired Flameless Oxyfuel at Rotary Hearth Furnace for Tube Production at ArcelorMittal

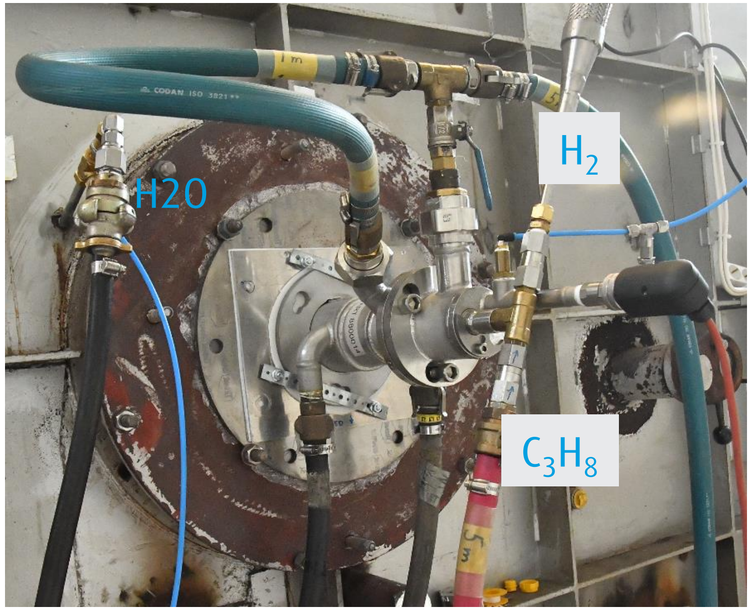
Hydrogen fired Flameless Oxyfuel at a Linde Technology Centre, Stockholm

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

- → Safety
- → Temperature Profile in the Furnace
- → Generation of NOx
- → Water Content in Flue-gas
- → Flue-gas Analysis
- → Scale Formation (surface oxidation)
- → Decarburization
- → Hydrogen Pick-up

Steel Reheating Tests with Hydrogen
Linde Technology Centre Stockholm, October 2019

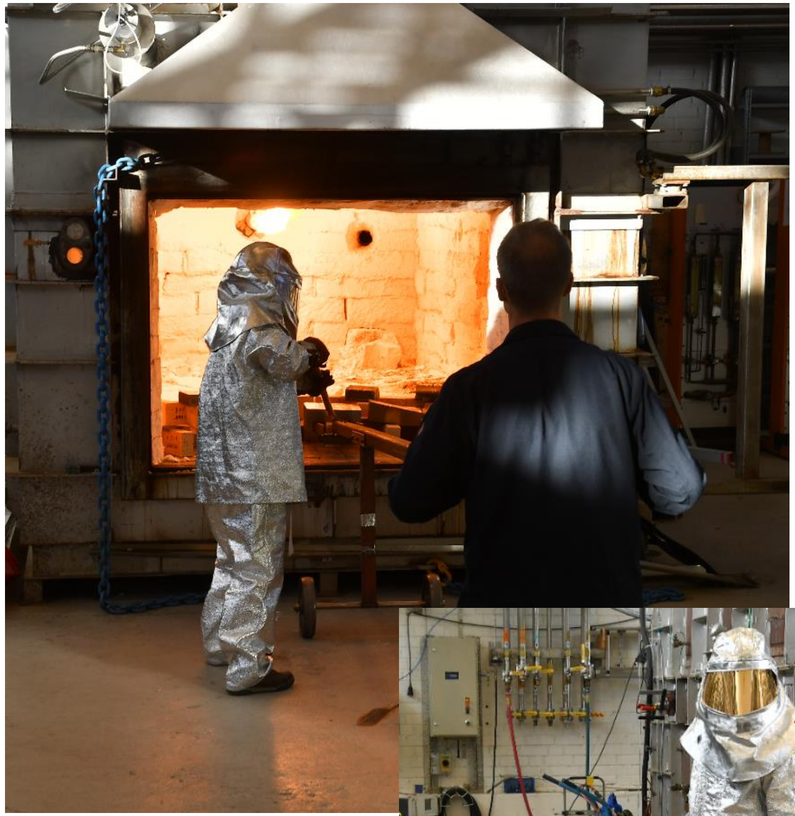


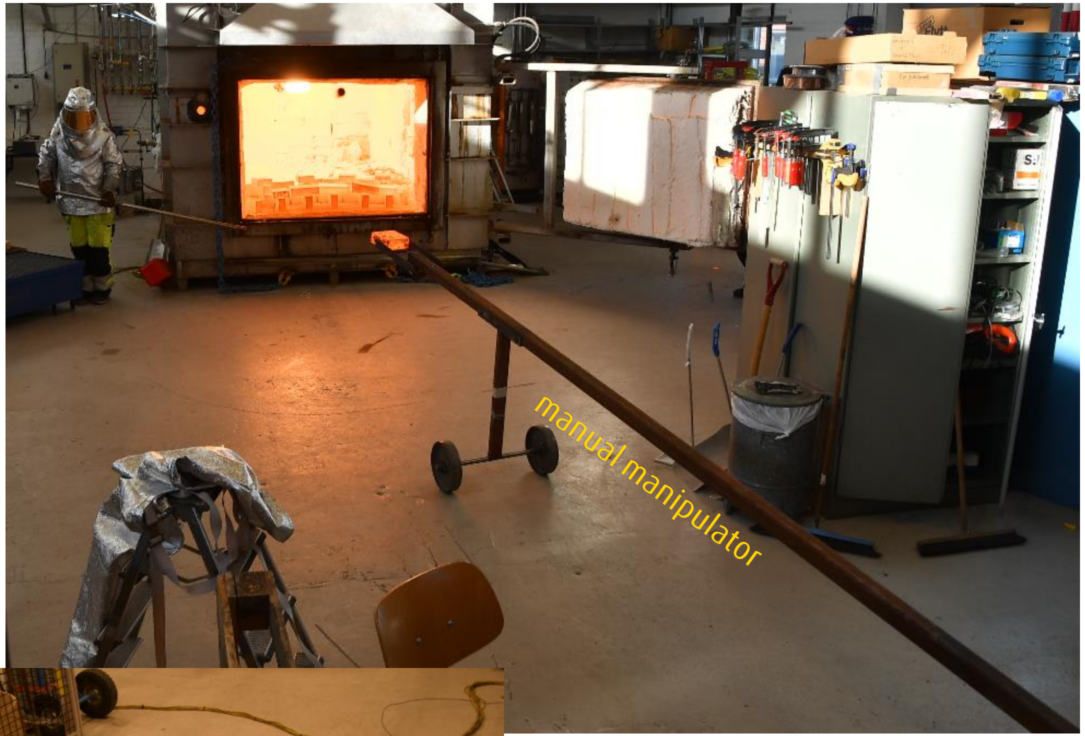


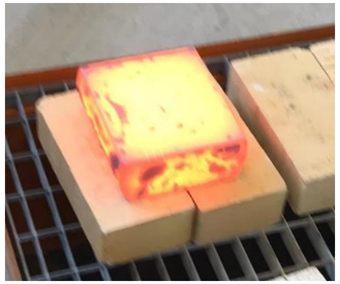
REBOX
Flameless Oxyfuel burner

Steel Reheating Tests with REBOX® Hyox

Linde Technology Centre Stockholm, October 2019

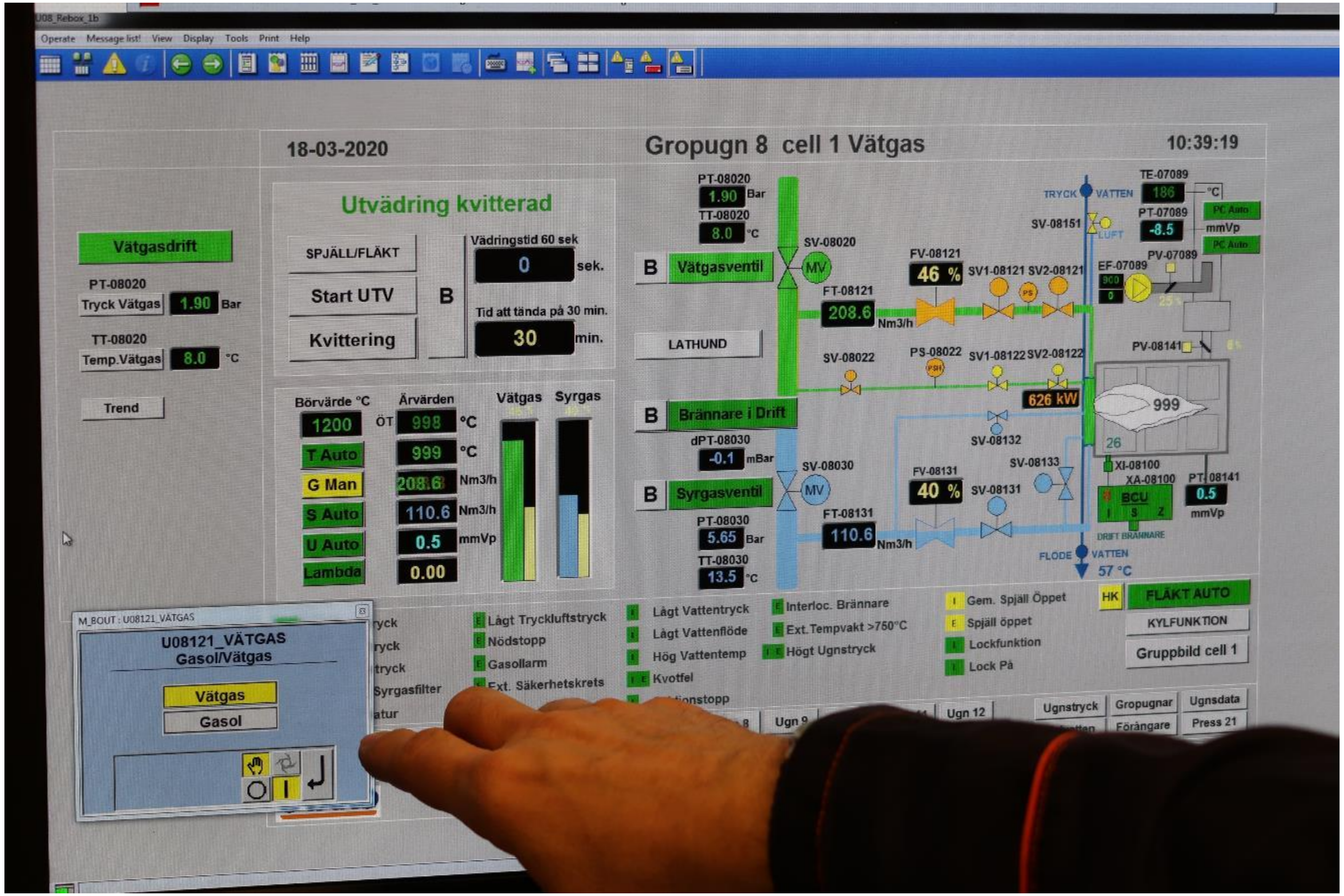






Material tested from four steel companies, including engineering steel and stainless steel grades

18th of March 2020: Ready for Full-Scale!
Ready to Switch from LPG to Hydrogen!



OVAKO

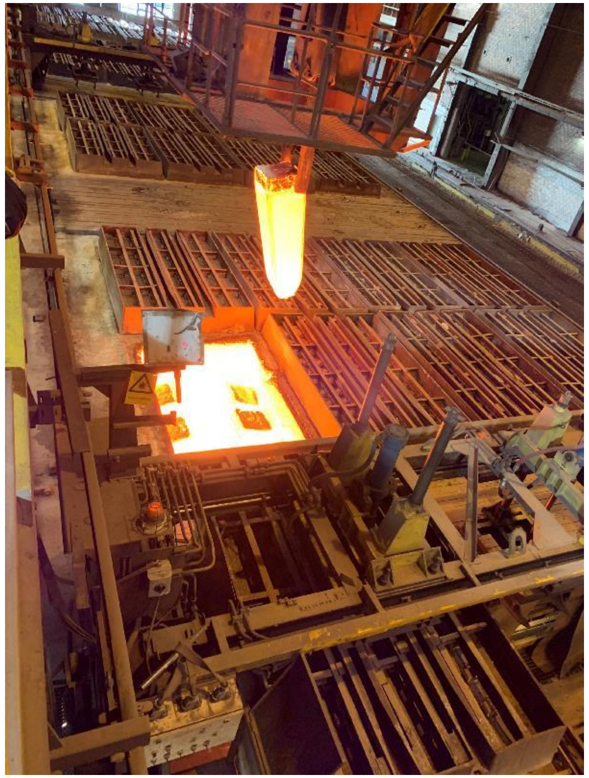
18th of March 2020: Charging Time!
Furnace running on 100% Flameless Oxyfuel with Hydrogen

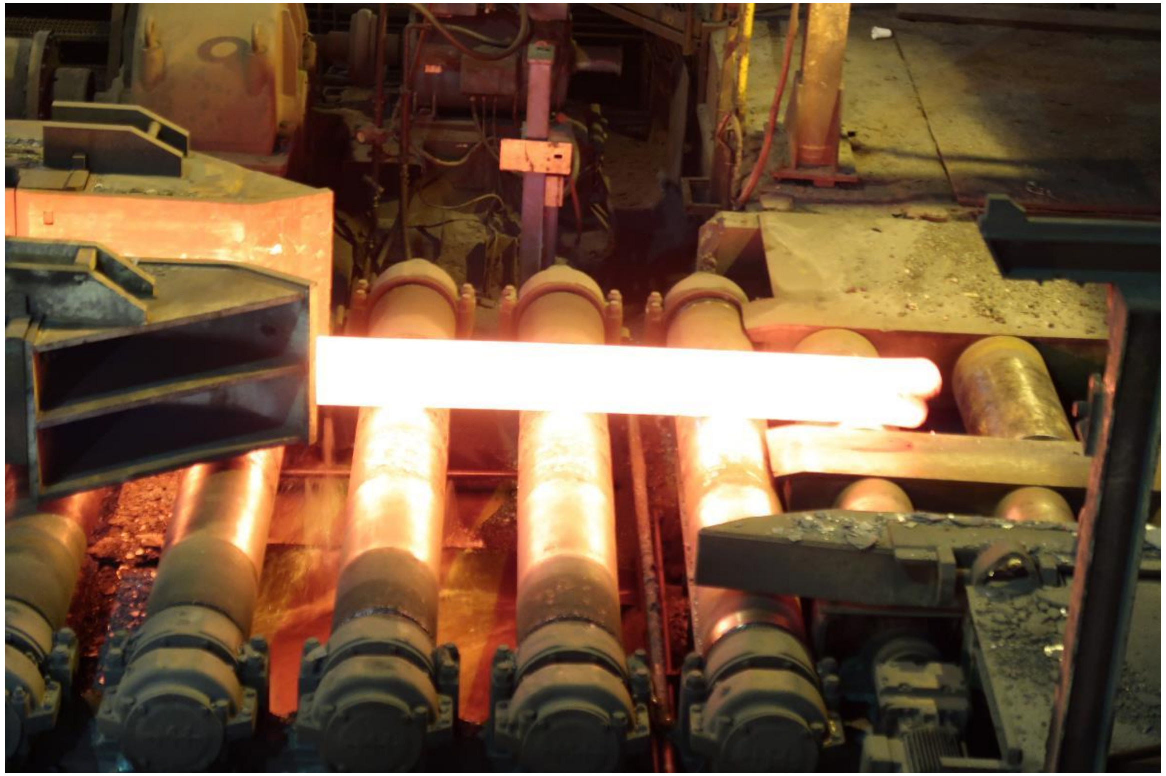
Four pit funaces, one with H2 and three with LPG. All same power, 650 kW.

Furnaces heated to 1200ºC before charging

6 x 4.2 ton ingots per pit furnace, all same ball bearing steel grade

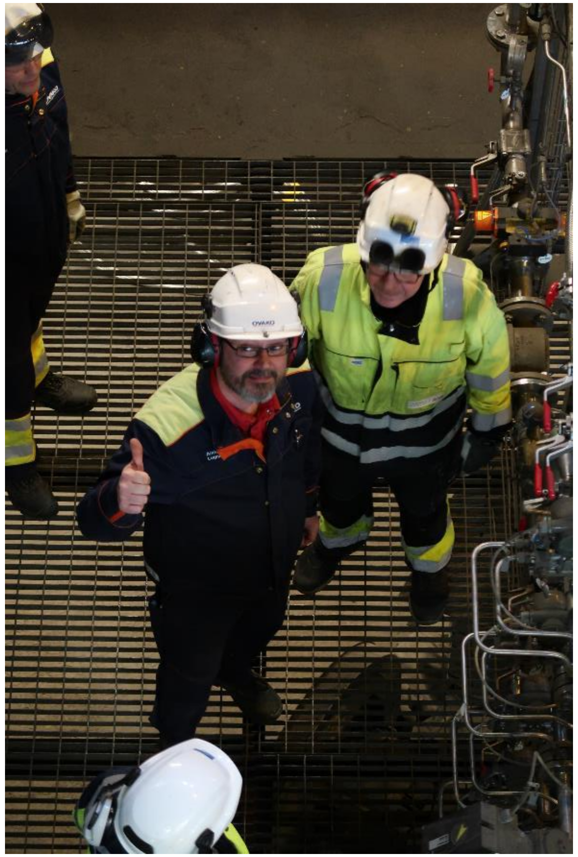
Discharging and Rolling of First Fossile Free Heated Steel Ingot in the World





Test Sampling, Steel on the Cooling Bed
After heated with 100% Hydrogen–Oxygen

Results of all quality tests shown OK and normal Hydrogen Can be Used in Full-scale Reheating!



"Hydrogen can be used simply and flexibly, with no impact on steel quality, which would mean a very large reduction in the carbon footprint."

Göran Nyström, EVP, Head of Technology and Marketing at Ovako

World's First Fossil Free Heated Steel

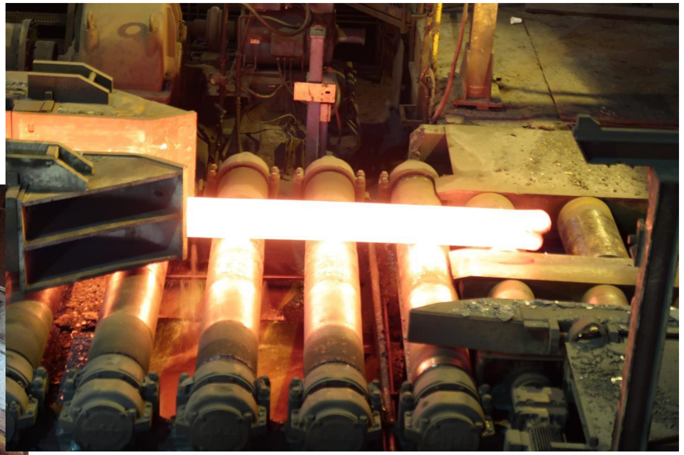
Linde

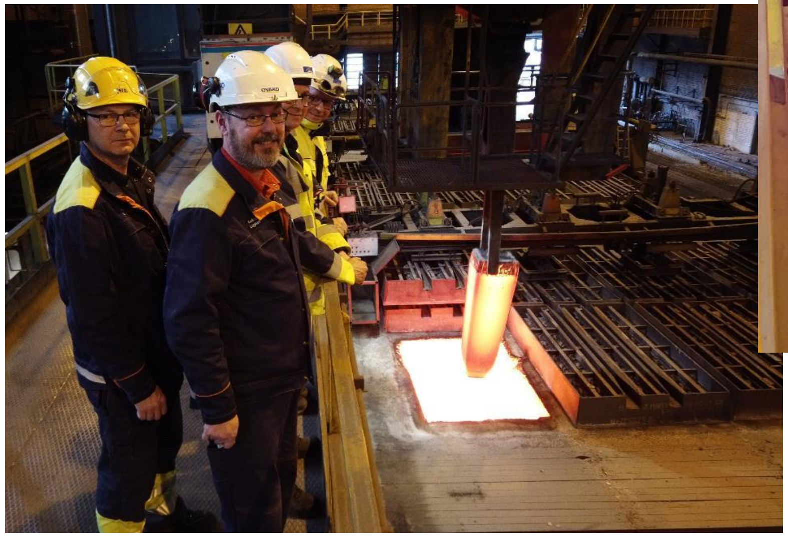
Ovako Steel, Hofors, Sweden
18th of March 2020

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

Both Hydrogen and Oxygen produced with Electricity from Renewable Energy sources

OVAKO



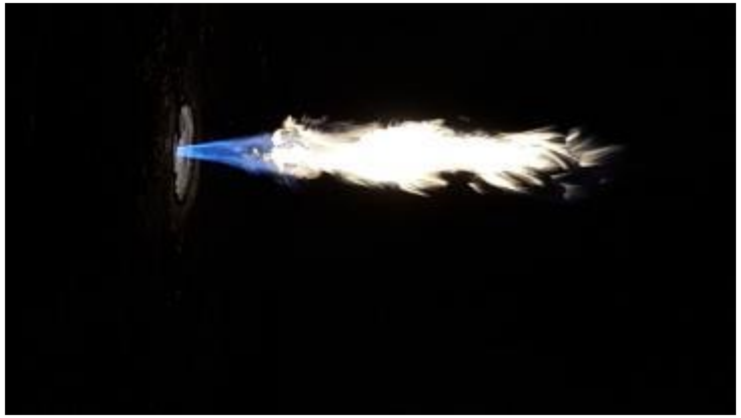


Full-scale permanent installation planned for 2022

H_2

OXYGON® Flameless Oxyfuel Ladle Preheating

200+ Installations Worldwide



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 when wanted (e.g., 1500ºC)
- Ultra low NO_x emissions
- Can operate with H_2 or mixtures of H_2 and other fuels; 100% H_2 can give 100% reduction of CO_2 emissions.

H_2

200+ OXYGON® Installations Worldwide

A World First in the Glass Industry!
Hydrogen Trials 2021 at NSG Pilkington, St Helens, UK

- NSG Pilkington began glass manufacturing at St Helens, UK in 1826 – a leading technology company in manufacture of float glass
- Produce ~5,600 ton/week
- 20 m long, 8 port cross-fired furnace firing Natural Gas

- Continuous supply of 2,000+ Nm^3/h of Hydrogen for up to 9 days
- Running up to 3,200 Nm^3/h of Hydrogen
- Two trial campaigns
  - 100% Hydrogen firing at Port 1
  - 15% Hydrogen blend at All Port positions

Decarbonisation and Use of Hydrogen in Reheat Furnaces
Summary

- Use of Flameless Oxyfuel decreases the fossil fuel consumption by 20-60%, and thereby also the future need for Hydrogen – a perfect transitional journey towards carbon-free production!

- Flameless Oxyfuel works well with Hydrogen as fuel, used partly or fully, still maintaining all its benefits including reduction of NOx emissions at Ladle Preheating, Steel Reheating.

- It has been demonstrated in full-scale production that reheat furnaces equipped with Flameless Oxyfuel can be operated with 100% Hydrogen without any negative impact on the steel heated. Permanent full-scale operation with 100% Hydrogen Flameless Oxyfuel combustion is expected to be commissioned in 2022.

- Three out of four of Linde's Technology Centres for combustion are already equipped for Oxygen–Hydrogen firing. Tests in laboratory and pilot scale of Hydrogen combustion will continue:
  - Technology for NOx measurement in high water vapour atmosphere should be developed.
  - Interesting potential for flue-gas condensation for heat recovery.

- Development and implementation of combustion technologies for use of Hydrogen as Fuel in Industrial Furnaces pace ahead of viable supply of Green Hydrogen.

Global Awards for
Steel Excellence

2021 FINALIST ENVIRONMENTAL RESPONSIBILITY STEWARDSHIP

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