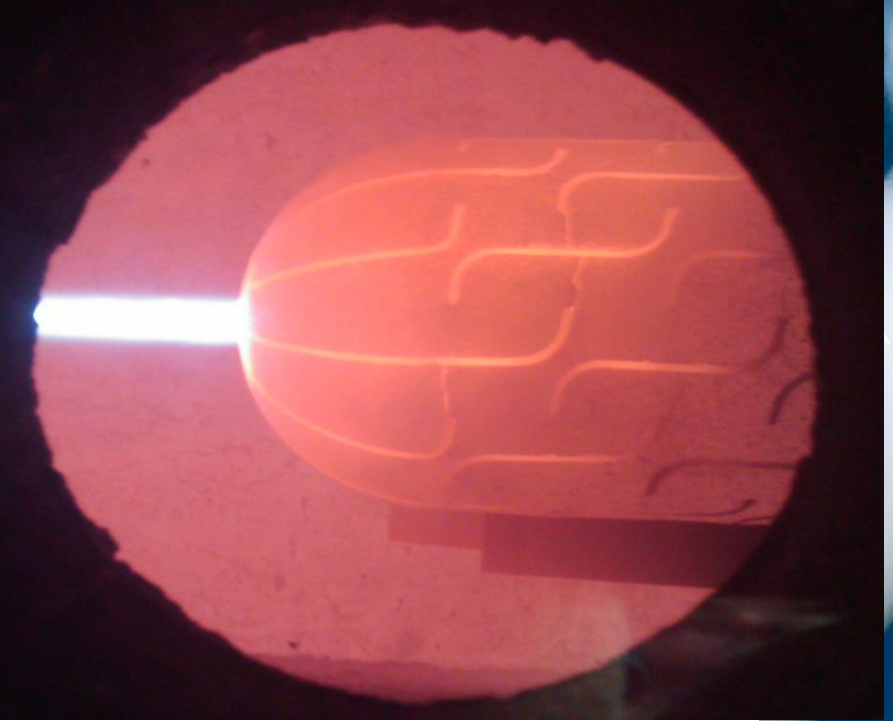



Viable Options for Decarbonisation and Use of Clean Hydrogen

CORALIS Workshop, 19th of December 2022

Joachim von Schéele

Making our world more productive

Linde – Gases and Technologies Supporting a Greener Future

World's Largest Industrial Gases Company

- Sales at €31 billion
- Market Capitalization at €160 billion
- Activities in 100+ Countries
- ~73,000 Employees
- 6,500+ Patents
- Investing >€1 billion per year in Clean Energy
- Both Gases and Engineering (EPC)

World-leading Supplier of Hydrogen

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

Provider of Carbon Capture Solutions

- Long track record as a supplier of carbon capture solutions
- Cooperation with BASF
- Cooperation with Schlumberger

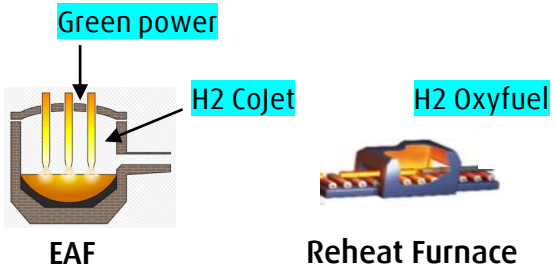
A General Approach to Decarbonisation

1. Increase the life-cycle of the products – a year longer in use saves a year of emissions from production
2. Increase the recycling rate – usually less negative impact compared to using virgin input materials
3. Electrify wherever it makes sense to electrify
4. Increase the energy-efficiency in processes that are not electrified
5. If possible, replace high-carbon containing fuels with a low-carbon containing fuels
6. Then, use hydrogen wherever it makes sense

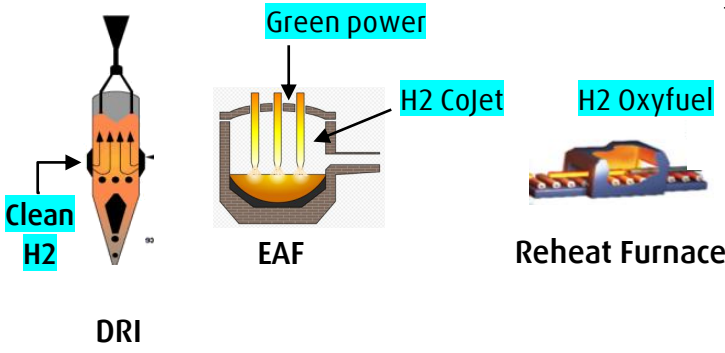
Hydrogen Requirements for Green Steel: Scale and Cost

X-Large Scale: From MW to GW

Minimill



Integrated DRI Mill



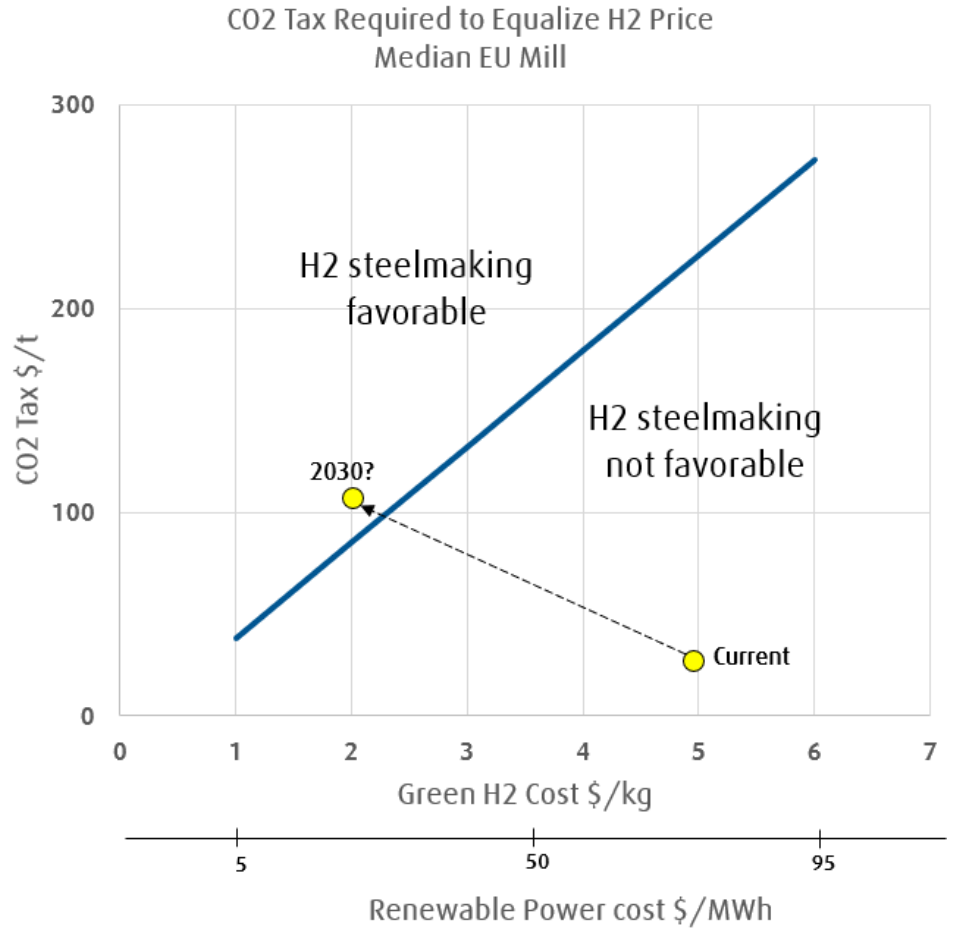
For 1 mm tpy production*

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

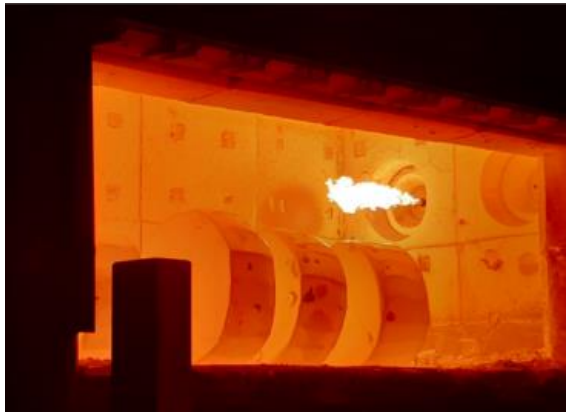
→ 200 TPD H2 / 475 MW electrolyzer + 100 MW EAF power

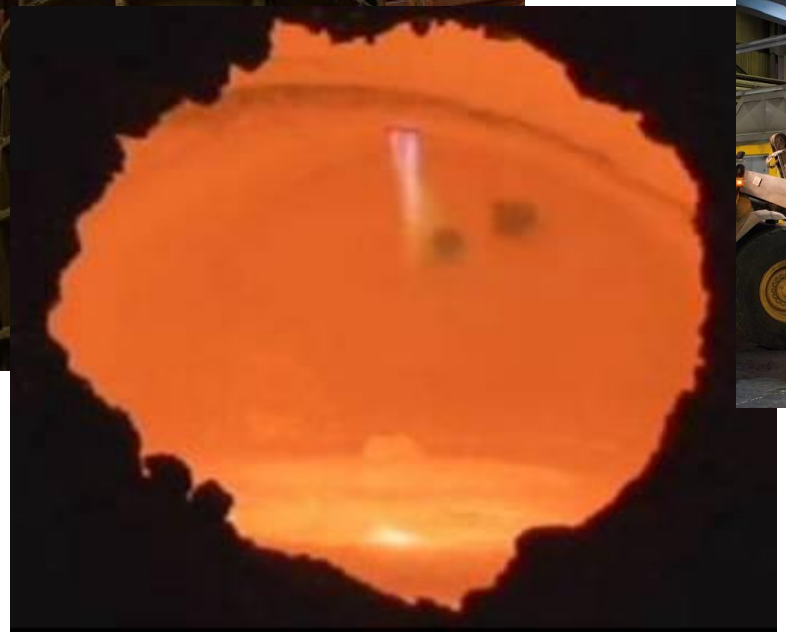
*Rough estimates for a typical operation

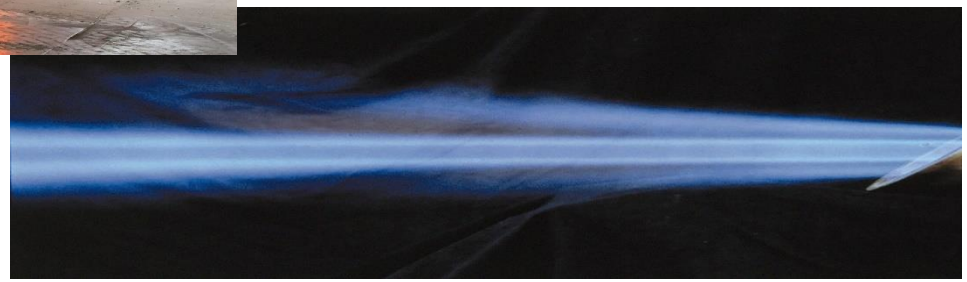
Costs: below $2/kg @ $100/t CO2 tax



Linde Technologies in the Metallurgical and Glass Industries: 800+ Oxyfuel Installations

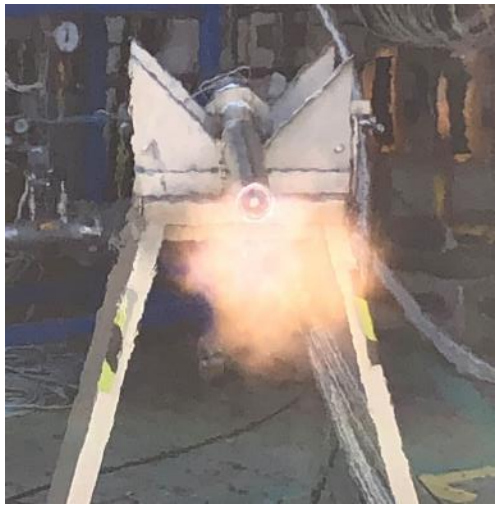






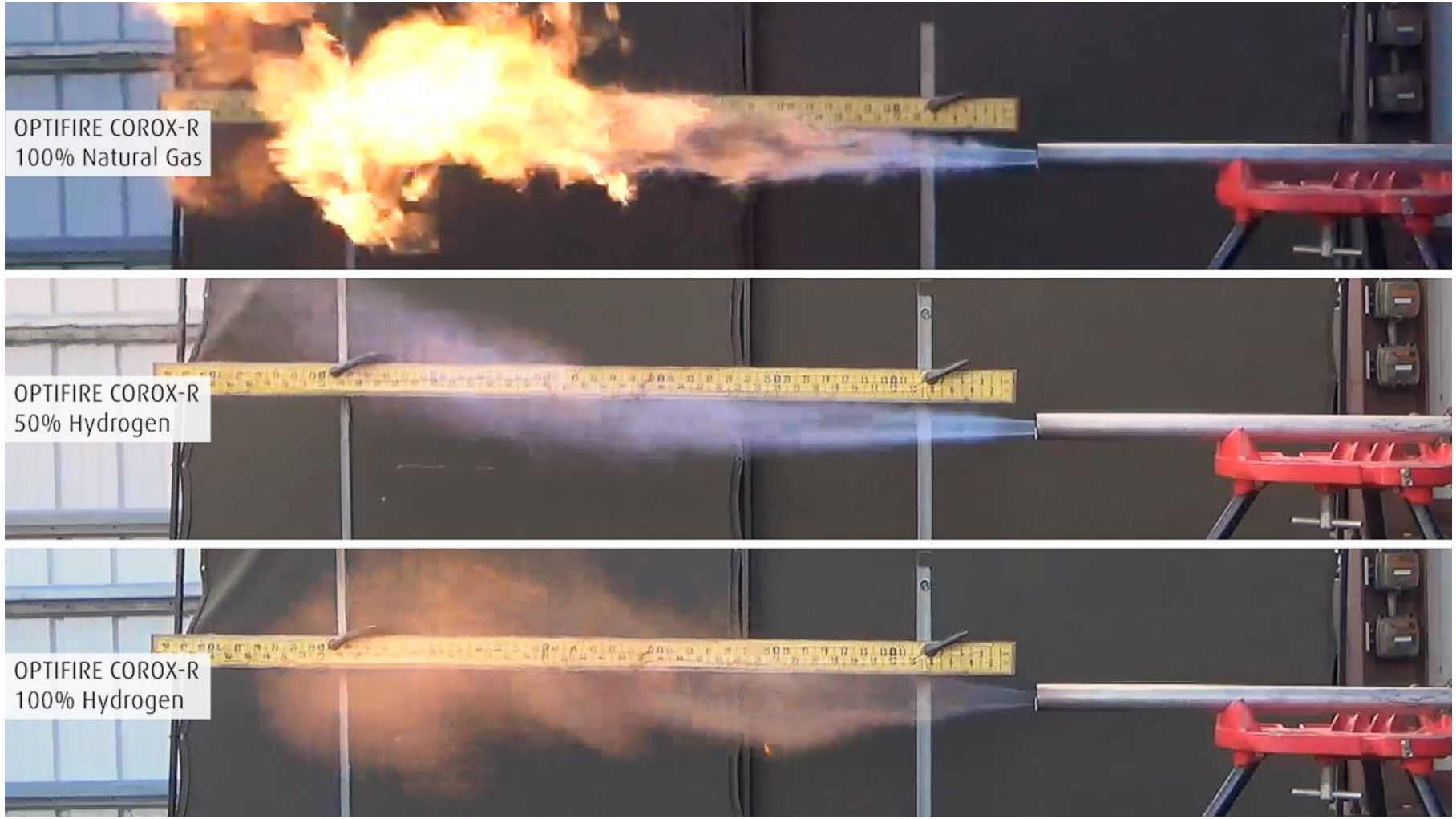
Linde Technology Centre Munich
Hydrogen-Oxyfuel Trials Spring 2019

Open air firing of 300 kW COROX burner for Glass melting



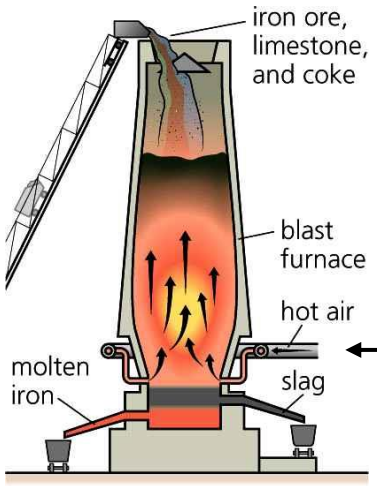
High concentration of Water Vapour creates infrared radiation

Hydrogen-Oxyfuel Trials at Linde Tech Centre, Tonawanda (US)



Gasification to Produce Low Carbon Fuels

Example: Hot Oxygen Technology

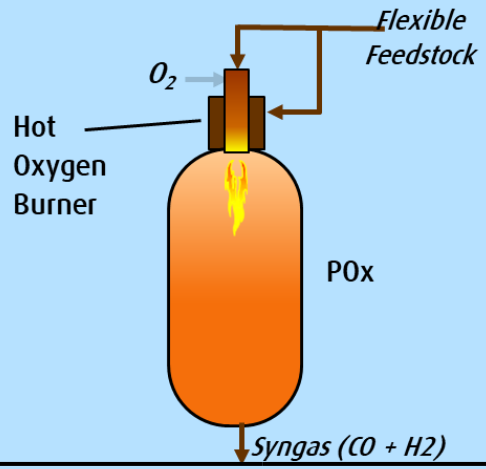


Blast Furnace

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

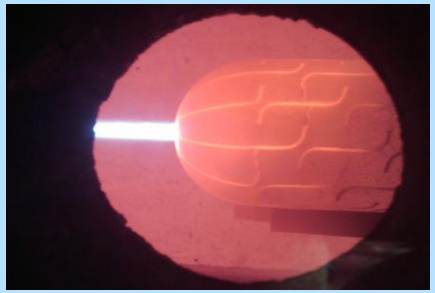
Linde's Hot Oxygen Technology

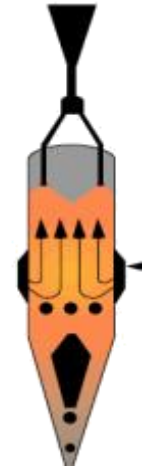
External Gasification of low carbon feedstocks



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

- Efficient, small-scale gasifier to generate *hot* syngas
- Up to 35,000 Nm^3/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

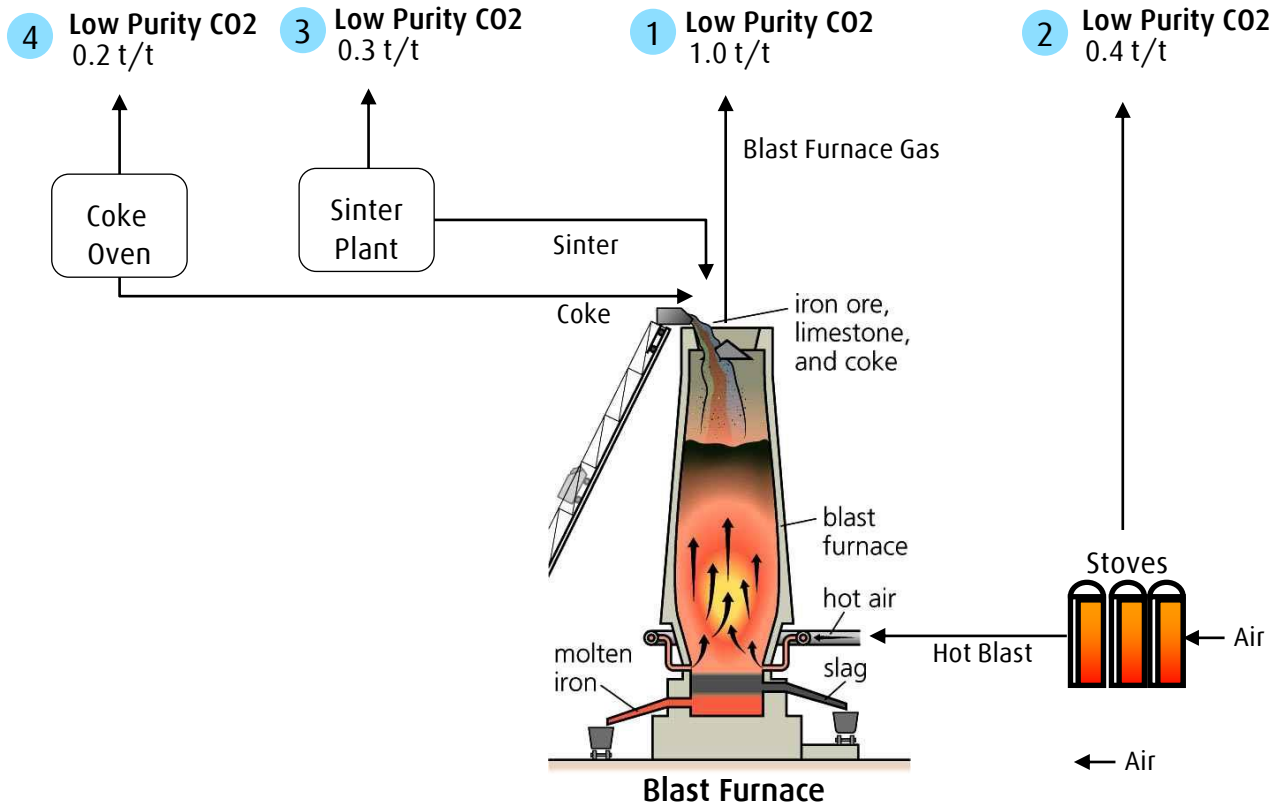
HOT installed at Fulcrum Sierra

Sierra Biofuels, Nevada

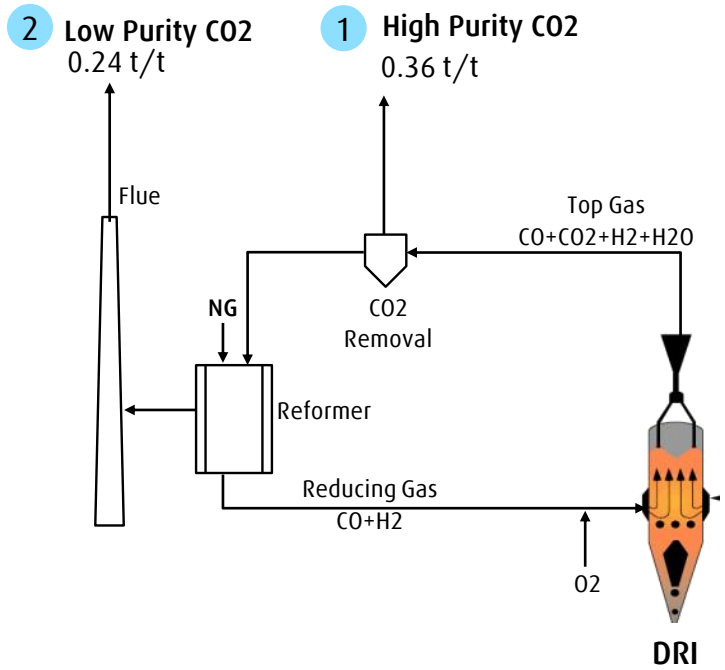
- Gasification of Municipal Solid Waste (MSW) to clean syngas
- 175,000 TPY MSW → 50,000 m3/y syncrude
- Gasifier hot commissioning in progress, full plant commissioning in preparation
- Production of Sustainable Aviation Fuel (SAF)

Carbon Capture

Multiple Points of CO_2 Emissions at Iron Ore Reduction

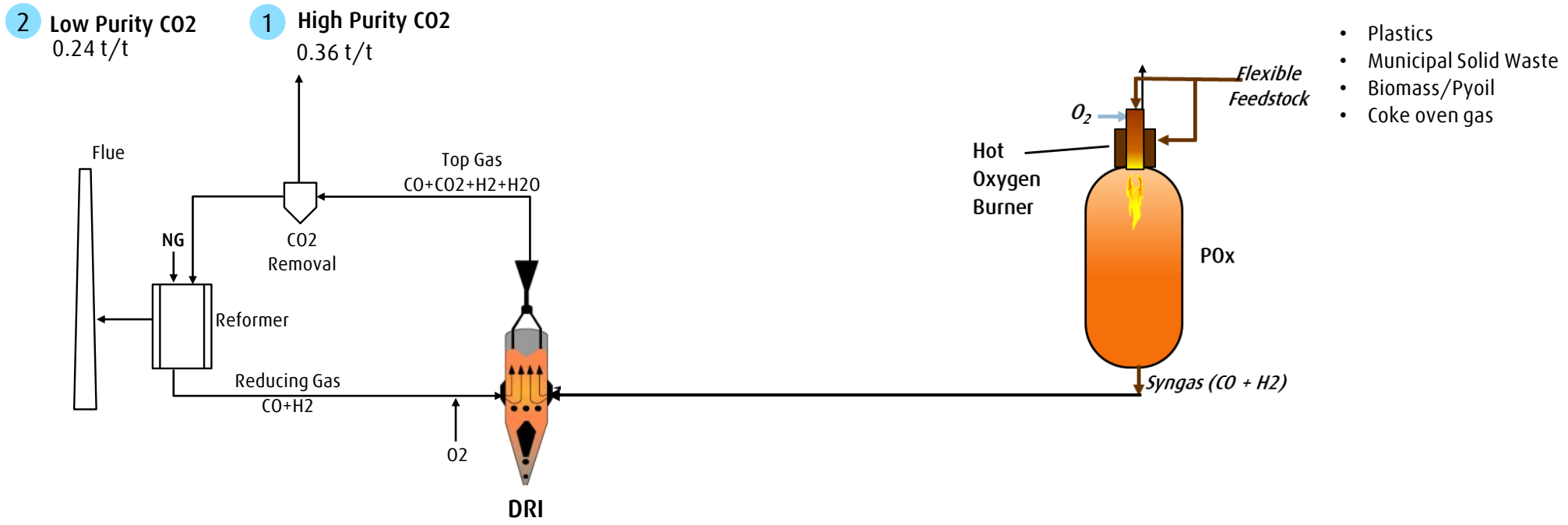


~1000 TPD CO_2 for 1Mtpy DRI



Natural Gas (or Coke Oven Gas) operating with Carbon Capture could Compete with H2-DRI

Combining Gasification with DRI Using Carbon Capture



When a viable supply of hydrogen is in place, hydrogen can be added.

Hydrogen Combustion Economics
Oxyfuel is a Prerequisite for Hydrogen Combustion

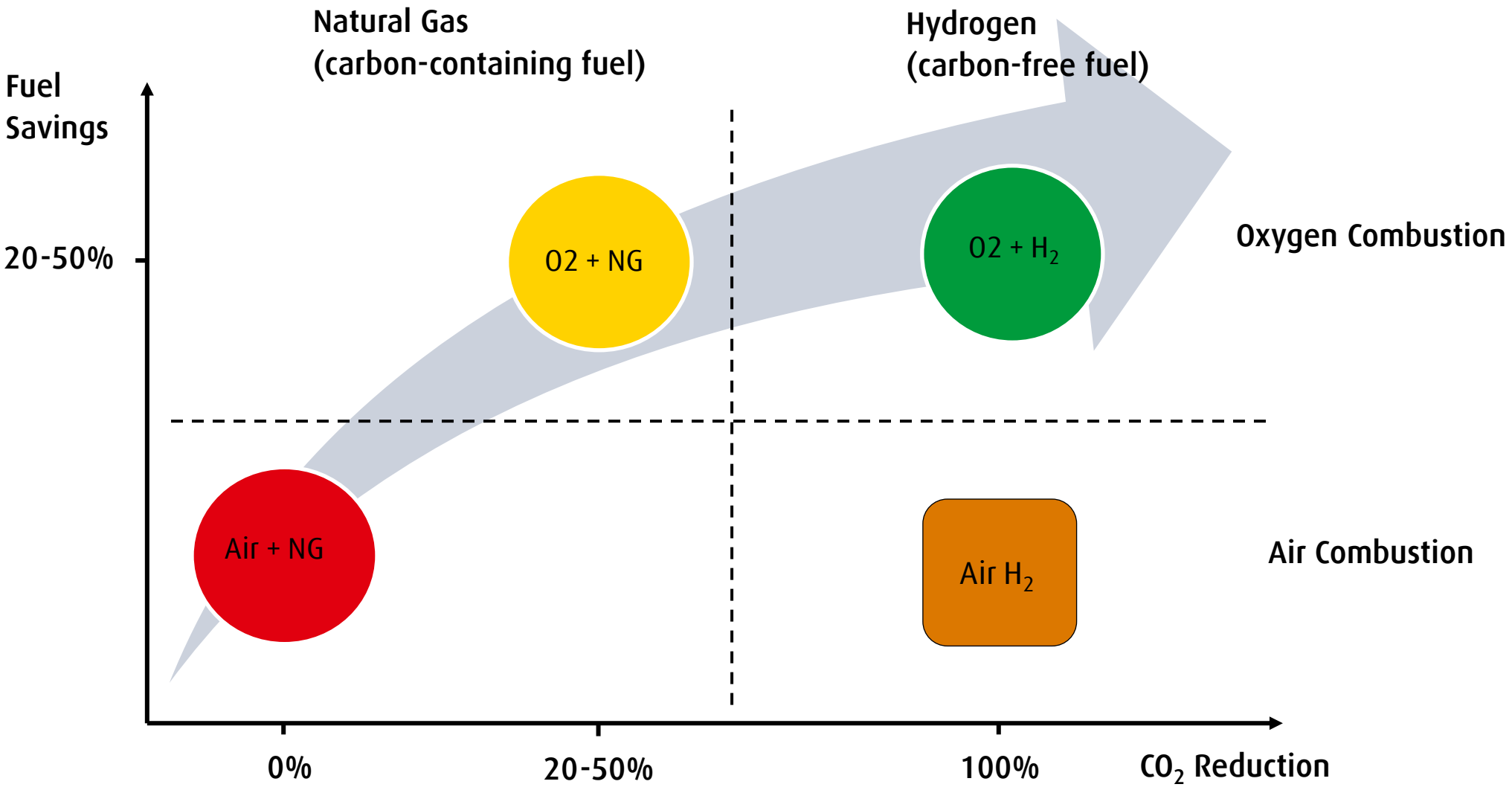
Hydrogen will be an expensive fuel

- 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** 20-60% CO_2 Savings ⇨ **Oxyfuel w/ H_2** Full Decarbonisation

Route to Decarbonize Industrial Heating Operations

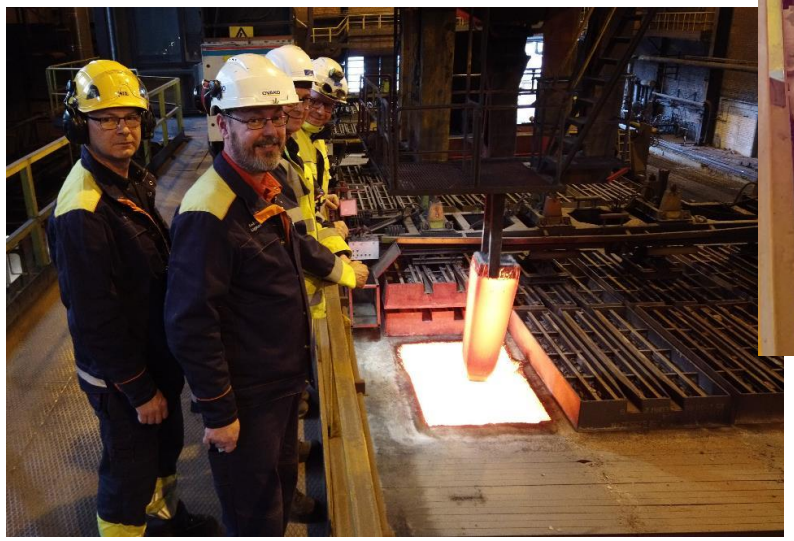


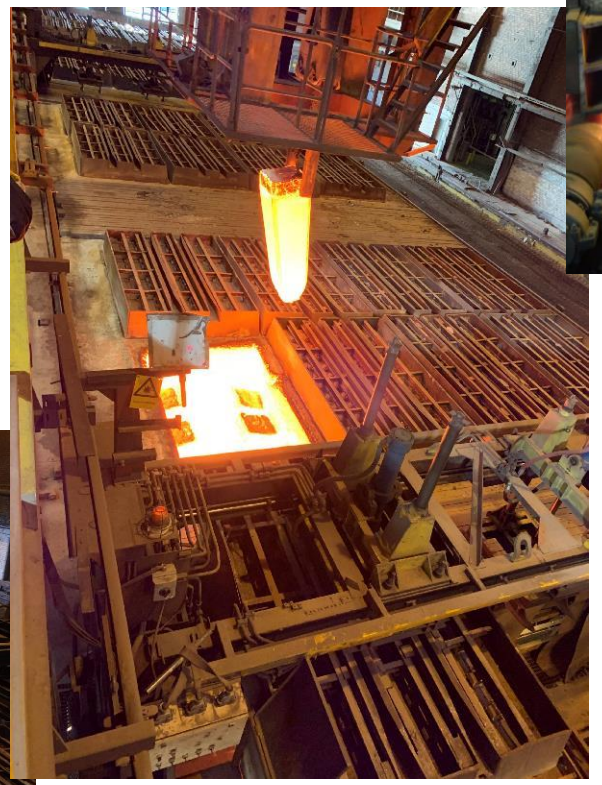
World's First Fossil Free Heated Steel

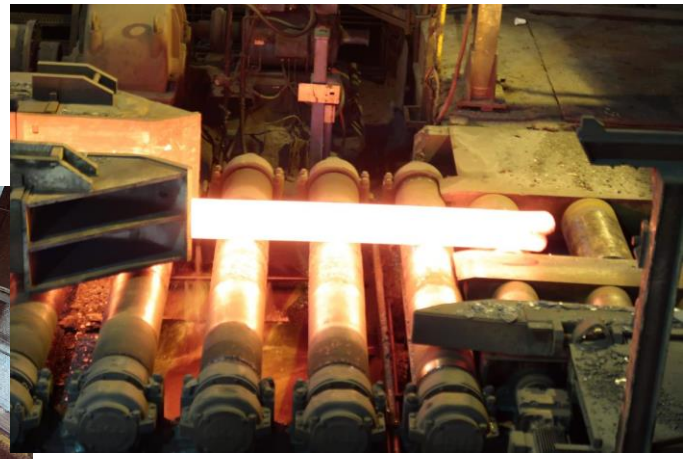
Ovako Steel, Hofors, Sweden
18th of March 2020

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 Q2 2023
24 Soaking Pit Furnaces
Saving 20,000 t CO_2 annually

H_2

OXYGON® Flameless Oxyfuel Ladle Preheating

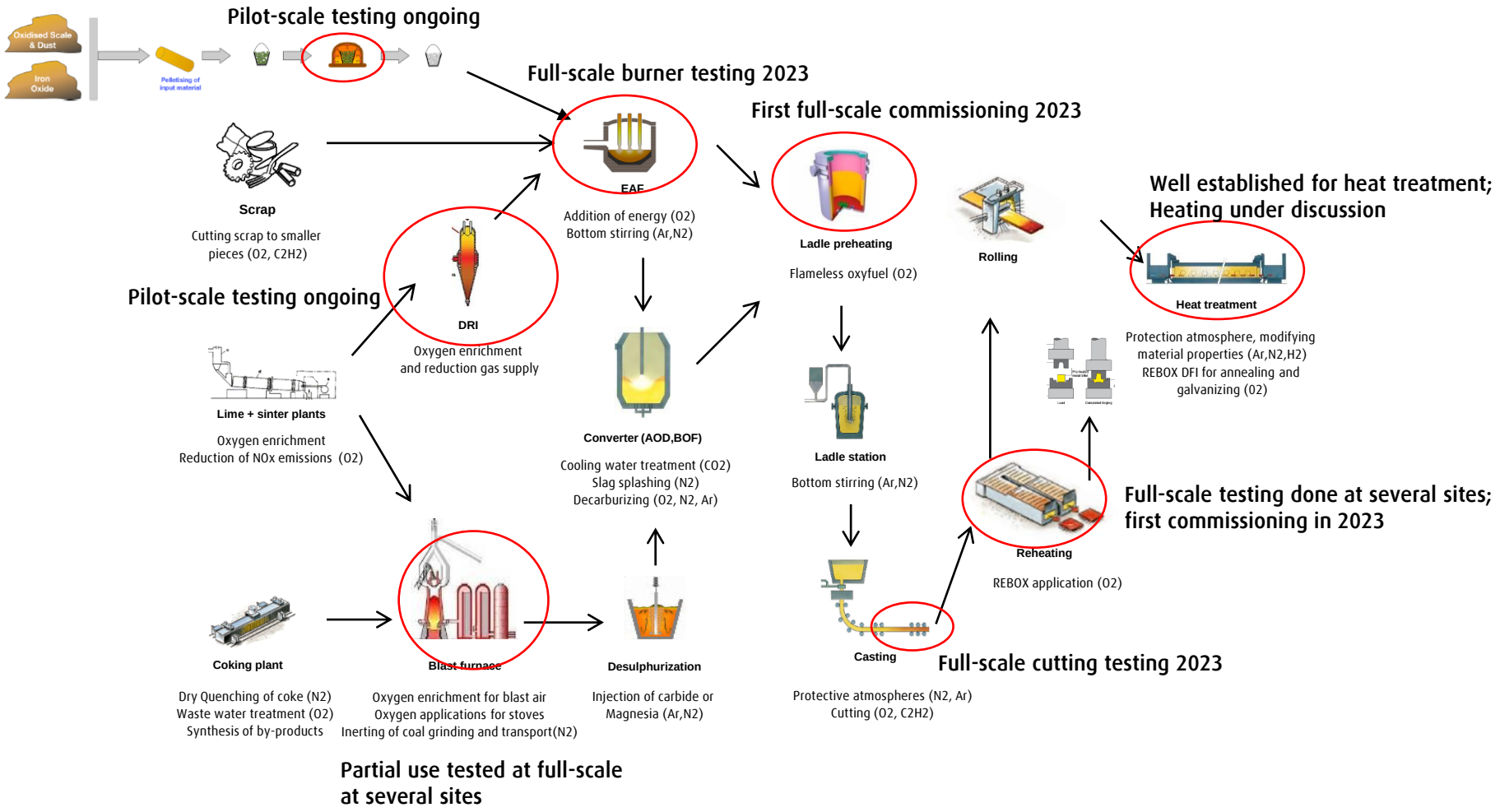
Ready for Using Hydrogen as Fuel

- 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., 1500°C); 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



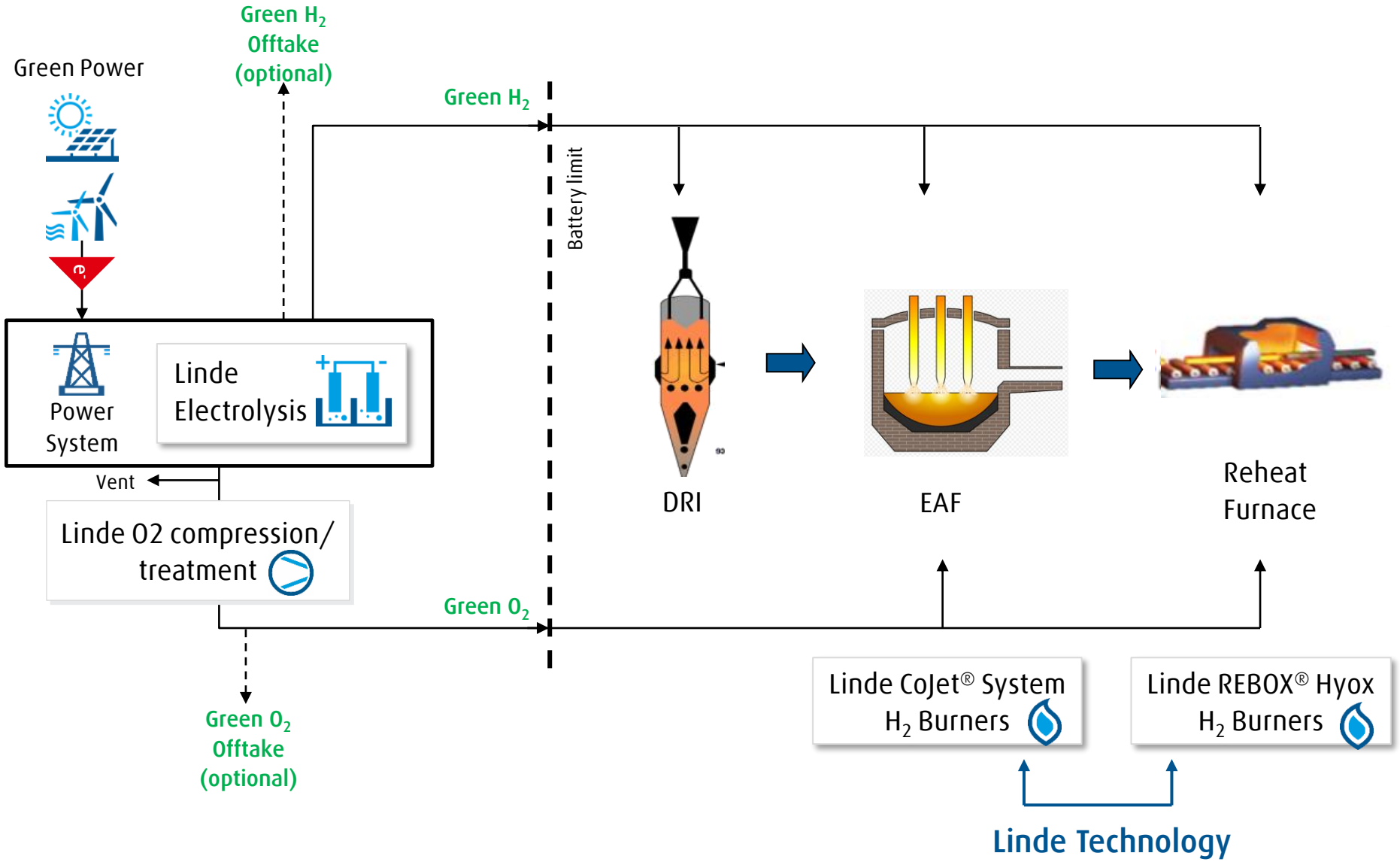
Near-term Activities, Multiple Solutions, Long-term Development Projects

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.

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:

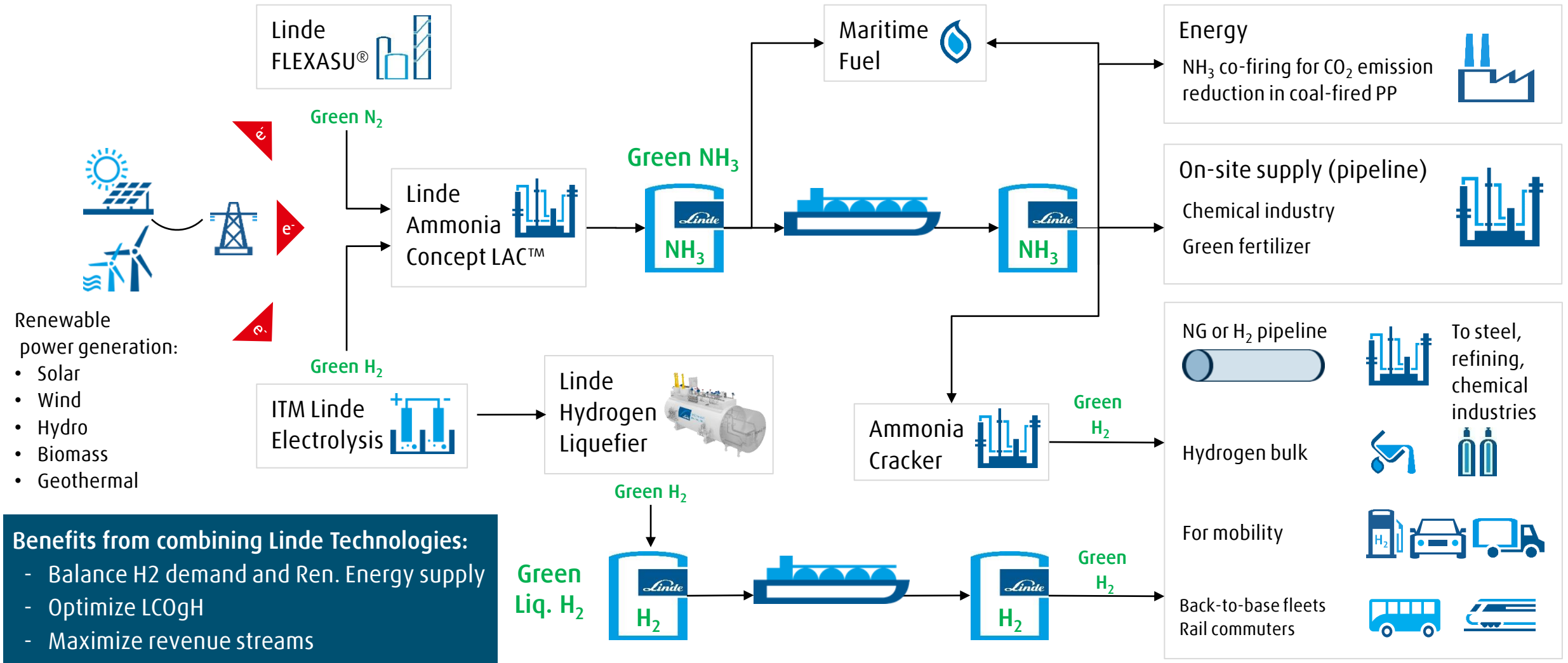
H2 and O2 Production	
Electrolyzer capacity	1.1 GW
H2 Production	210,000 Nm3/h
O2 Production	100,000 Nm3/h

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

H_2 Value Chain for Intercontinental Applications

Example of an integrated production plant for green ammonia used as energy vector



Benefits from combining Linde Technologies:

- Balance H2 demand and Ren. Energy supply
- Optimize LCOgH
- Maximize revenue streams
- Develop (new) sustainable biz models

Thank you for your attention!

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Making our world more productive