Integrated Hydrogen Supply for Steel Decarbonization

Todd Skare

Chief Technology and Sustainability Officer

Making our world more productive

Introduction to Linde

- The leading industrial gases and engineering company
- Formed in 2018 with the merger of Linde AG and Praxair, Inc – two world-class companies with nearly 140 years of shared history and successful achievements
- Proven critical project execution knowledge in diverse geographies
- Best-in-Class Safety Performance

One Linde

Uniting with a shared Vision, Mission and Strategic Direction, and demonstrating our Values and Behaviors in everything we do

2 million+

customers

Establishing a more diverse and balanced portfolio

100+

countries

Enabling strong, complementary positions in all key geographies and end markets

~80,000

employees

Achieving our full potential, individually and collectively

$8 million

charitable giving in 2019

Supporting our communities through contributions and employee volunteerism

6,500+

active patent assets worldwide

Leading with innovative products, solutions and technologies

RECOGNITION

MEMBER OF

Dow Jones Sustainability Indices

SAM

a RobecoSAM brand

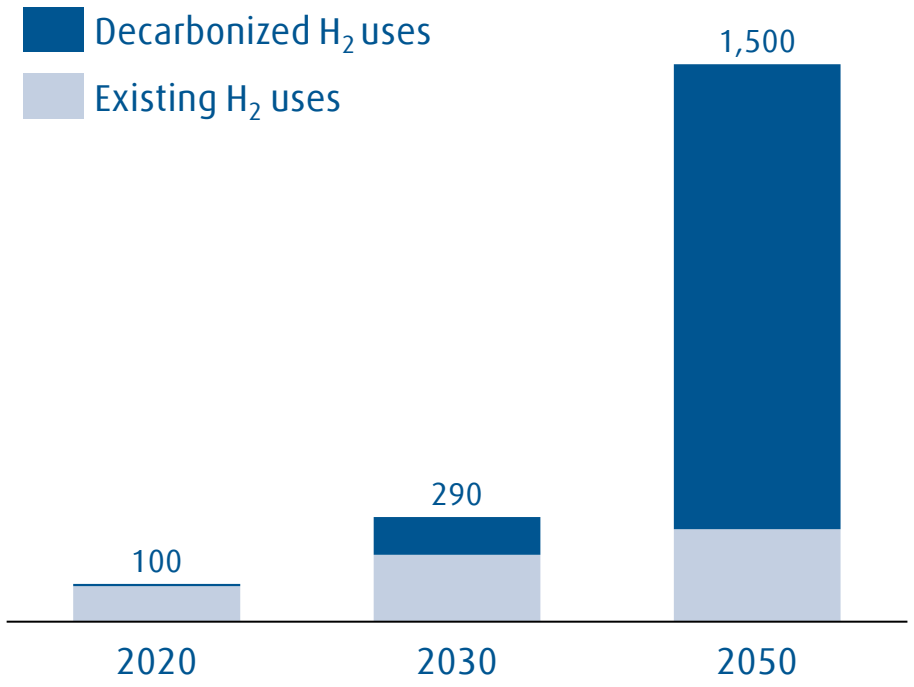
included in ETHIBEL SUSTAINABILITY INDEX EXCELLENCE Europe

2020 Bloomberg Gender-Equality Index

Clean Hydrogen Outlook

Demand will grow, fueled by the clean energy transition

Market Growth ($B)



Long-term market potential by application

Selected use cases	Adoption rate scenarios	Potential
Methanol	5% of global production	$6B
Trucks	1% of global fleet (ca. 150K)	$20B
Cars	1% of global fleet (ca. 10MM)	$7B
Heating	2% replacement in EU natural gas	$4B
Power	2% of RE converted for H_2 buffering	$15B

Substantial growth projected for hydrogen, although extent and timing still uncertain

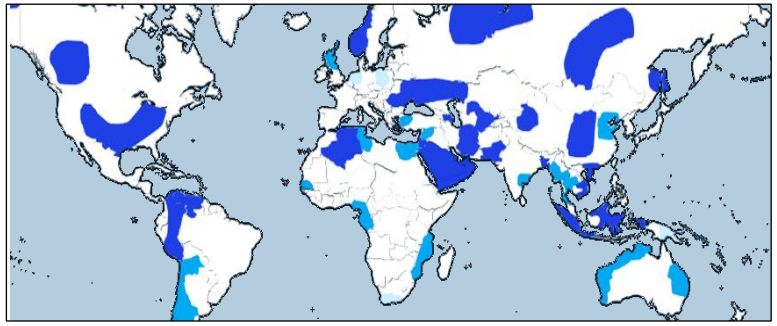
Source: H2 Council, BNEF, Linde Analysis.

The Hydrogen Momentum

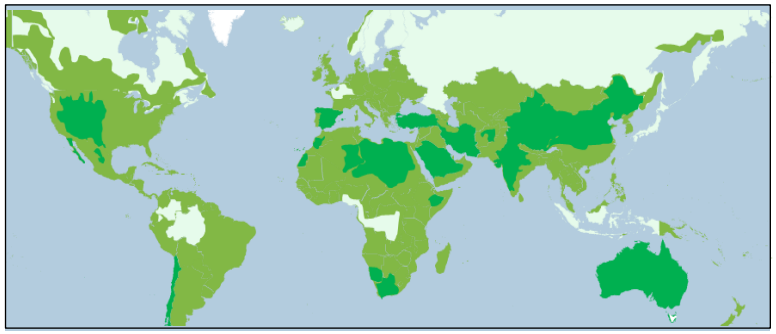
Color heavily influenced by natural resources and government support

Natural resources

Natural gas for Blue H_2



Solar & Wind for Green H_2



Source: H2 Council, McKinsey

Government support for Clean H_2

- **Green New Deal:** 200K vehicles and 450 HRS by 2025
- **$10.7B**[1] for eco-friendly future mobility until 2022

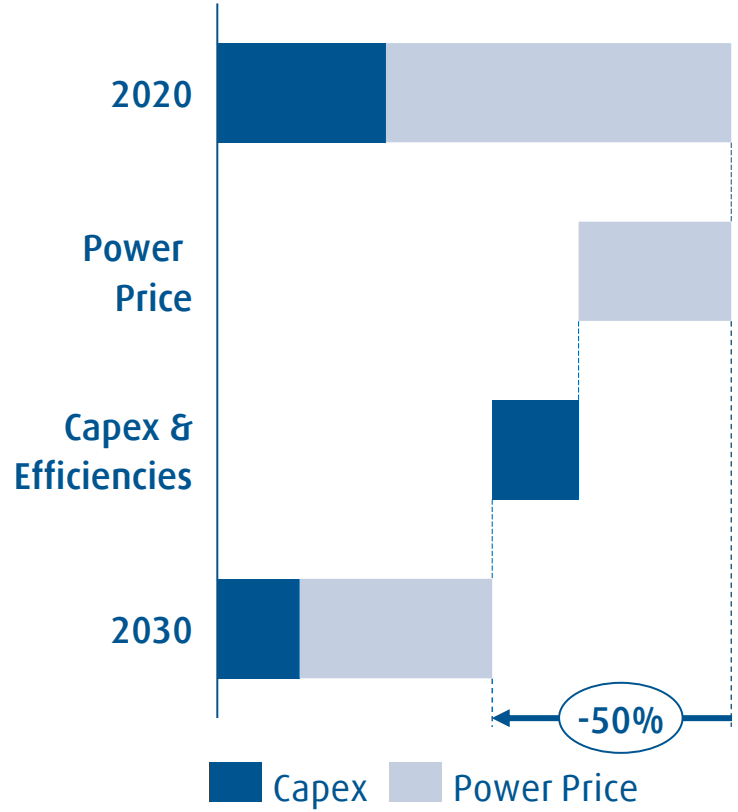
- **Low Carbon Fuel Standard:** California $200/t GHG
- 1MM FCEV and 1K HRS by 2030
- New California Executive Order: **no sales of new ICE cars after 2035**[2]

- **€7+2 bn** public support for H_2 deployment
- 5 GW by 2030

PEM electrolysis cost evolution

$/kg

Illustrative Example: Germany



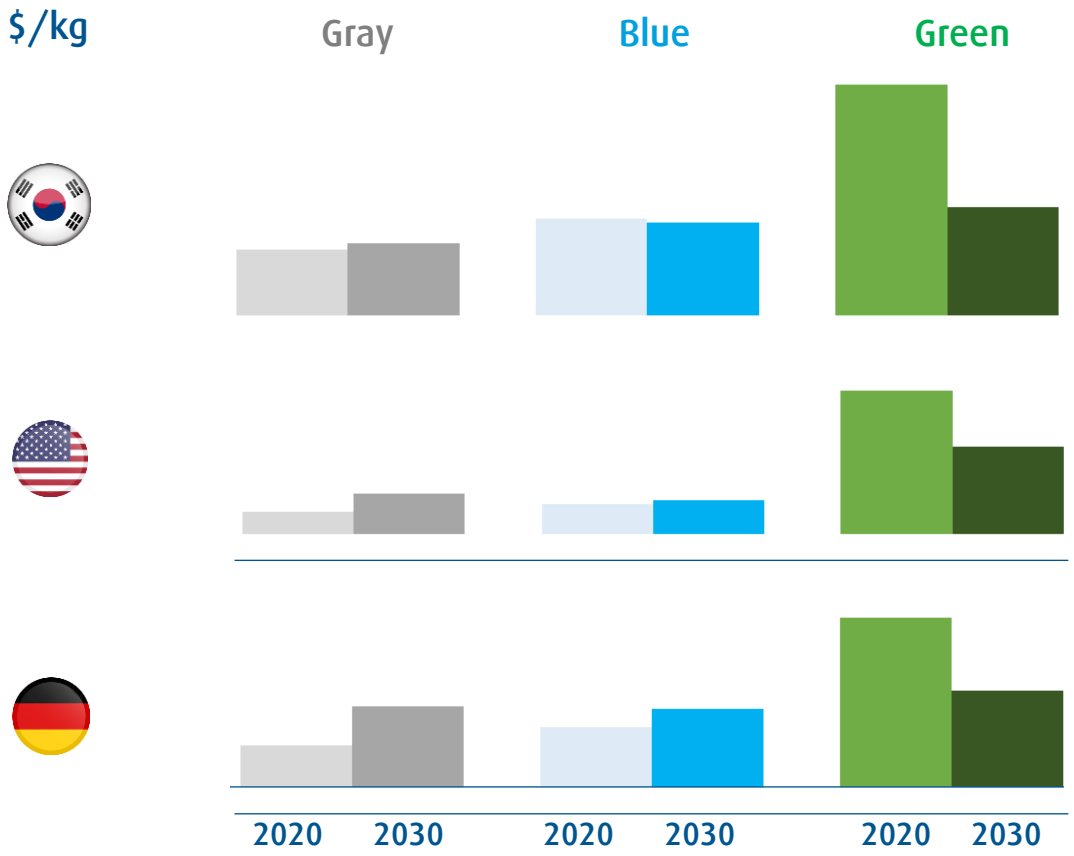
[1]Eco-friendly future mobility (deployment of EV & FCEV + earlier retirement of diesel vehicles/trucks)

[2] ICE Stands for internal combustion engine. All new medium-and heavy-duty trucks to be zero-emission by 2045.

The Hydrogen Momentum

Choice of hydrogen color will likely differ by geography

Local production costs comparison by H_2 type



Cost drivers

Gray H_2

- Price of natural gas
- Potential carbon taxation

Blue H_2

- Price of natural gas
- Carbon Capture & Storage (CCS) costs

Green H_2

- Power costs (renewable price and load factor)
- Electrolysis capex

Competitiveness of hydrogen color dependent on local policy framework and access/price of natural resources

Source: Linde

The Hydrogen Value Chain

Linde as integrator across the entire value chain

Production

- SMR, ATR, POX, …
- …with CCU/S
- Ammonia & methanol plants
- Electrolysis

Distribution

- Liquefaction
- H_2 refueling stations
- Trailers
- Underground storage
- Pipelines
- Equipment & Tech Offerings

Application

- Industrial
- Mobility
- Building & industrial heat
- Power

Gray H_2 Blue H_2 Green H_2 H_2 Distribution, Conditioning & Application

Ability to leverage existing infrastructure, technology & expertise – agnostic to the color of the molecule

Hydrogen production with PEM electrolysis

GLOBAL GREEN GAS SOLUTIONS | ITM LINDE ELECTROLYSIS

World class technology for green industry feedstock and storage

JV
GLOBAL GREEN GAS SOLUTIONS | ITM LINDE ELECTROLYSIS

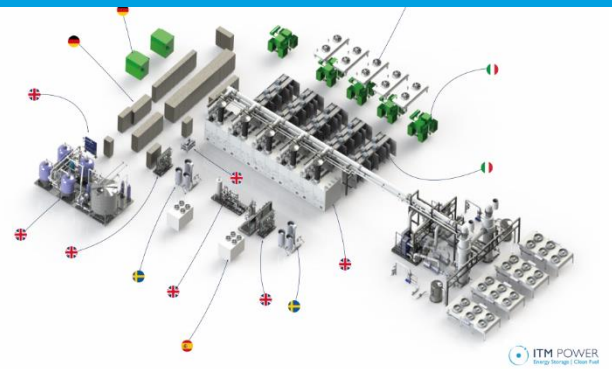
ITM POWER
Energy Storage | Clean Fuel

The leading OEM for PEM electrolysis technology

Linde Engineering

The leading Hydrogen and Syngas EPC firm

Industry



Example: Shell REFHYNE project

- 10 MW Electrolysis system for H2 generation (modular approach 5 x 2MW)
- Solid water treatment management system to expand life-time of electrolyzers
- H2 purification to 5.0 purity, suitable for load and grid balancing

Energy storage

Example: Energie Park Mainz

- Largest P2G plant, converting wind power into green hydrogen through electrolysis
- On-site production and storage of GH_2
- 800 kg storage (25 MWh)
- Running since 2015

Scaling Up Green Hydrogen
World class PEM electrolysis technology

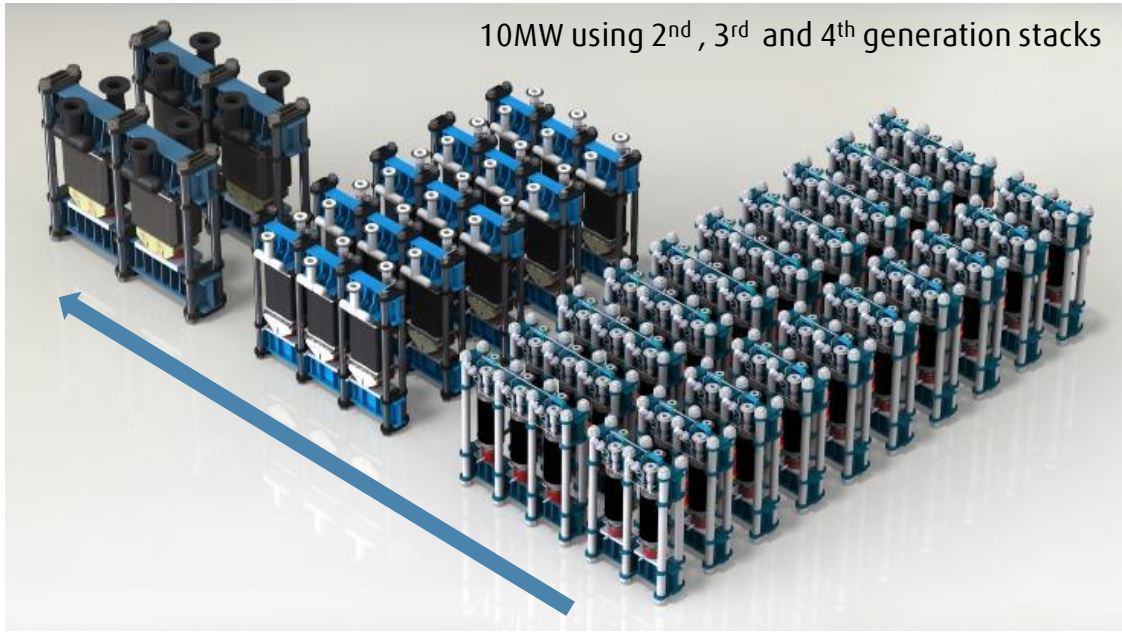
GLOBAL GREEN GAS SOLUTIONS | ITM LINDE ELECTROLYSIS

Linde

Upscaling: focused on simplification, footprint improvement and cost reduction

Manufacturing at ITM Power Gigafactory has started

At 1GW/yr it's the world's largest electrolyzer production facility.



Upscaling from 50 to 15 to 4 stacks for a 10MW module

- Design integration techniques reduce BoP costs
- Cells with significant efficiency improvement
- Acceleration plan to address market demand

Carbon capture, utilization and storage (CCUS)

Lowering GHG emissions

CO_2 capture in IG production
from SMR, ammonia, ethylene, steel & ethanol plants

Various **pre-combustion capture** as well as **post combustion capture technology options** available

CO_2 production for the **merchant market** & **large industrial consumers** (e.g. urea production)

CO_2 capture & utilization
for customer applications

CO_2 mineralization in concrete
Ready-mix & precast concrete application

CO_2 utilization in Greenhouses
Linde OCAP pipeline in The Netherlands

CO_2 utilization for water pH control & remineralization
Linde SOLVOCARB technology for wastewater & drinking water

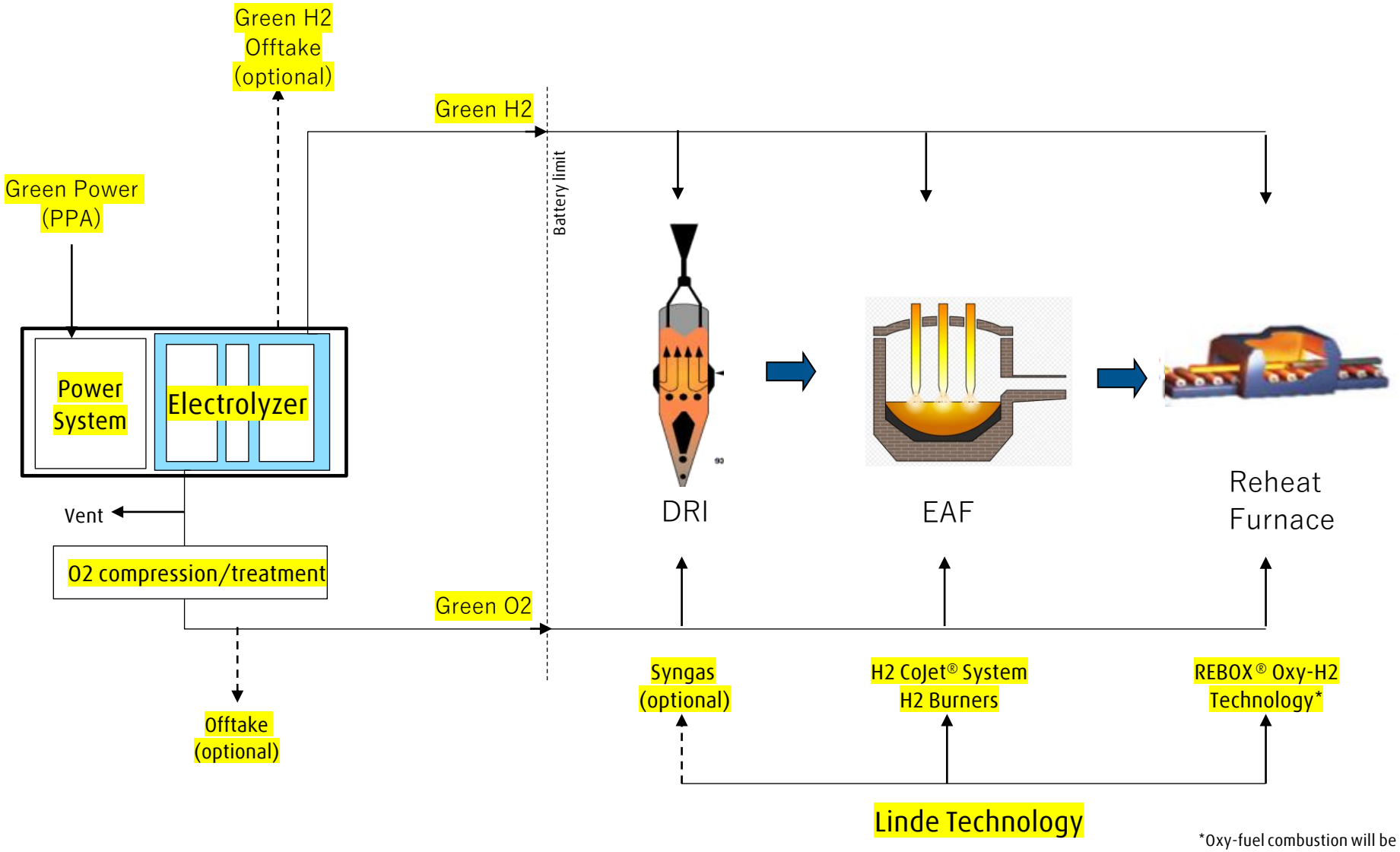
CO_2 capture & utilization technology
for IG production & customer applications

Linde DRYREF™
dry methane reforming for chemicals production with external CO_2 import

Linde post-combustion capture & purification
for hard to decarbonize industries (e.g. cement, steel)

Linde oxyfuel combustion capture & purification
for industry decarbonization (e.g. power, cement, glass)

Linde Integrated Hydrogen Supply
DRI-EAF steel plant



*Oxy-fuel combustion will be economical/required with H2

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

H2 and O2 Production	
Electrolyzer capacity	950 MW
H2 Production	68.5 kg/t 190,000 Nm3/hr
O2 Production	500 kg/t 90,000 Nm3/hr

H2 and O2 Consumption				
	DRI	EAF	Reheat	Total
H2, kg/t	54	2.5	12	68.5
O2, kg/t	0-55	45	30[1]	75-130[2]

[1] for partial oxyfuel conversion of reheat furnace. Full conversion will require 2x

[2] ~25% of electrolyzer O2 production is used

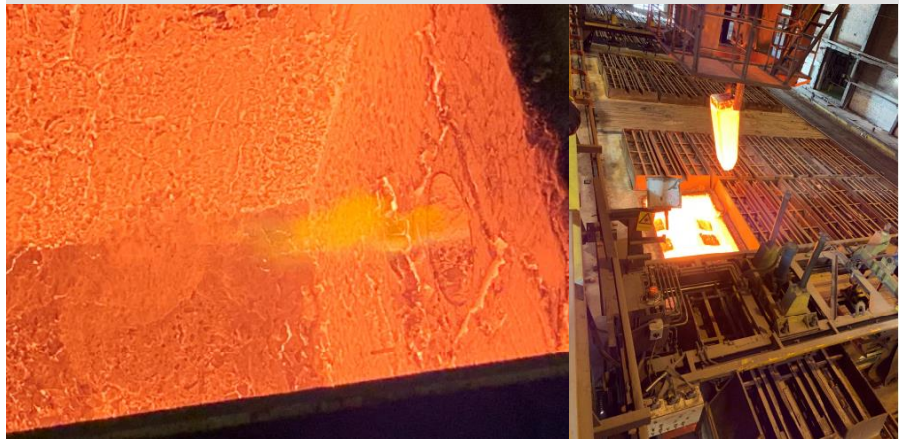
Incremental Steps to Net Zero: *Energy Efficiency with Oxyfuel Combustion*

Over 170 REBOX® oxyfuel installations worldwide

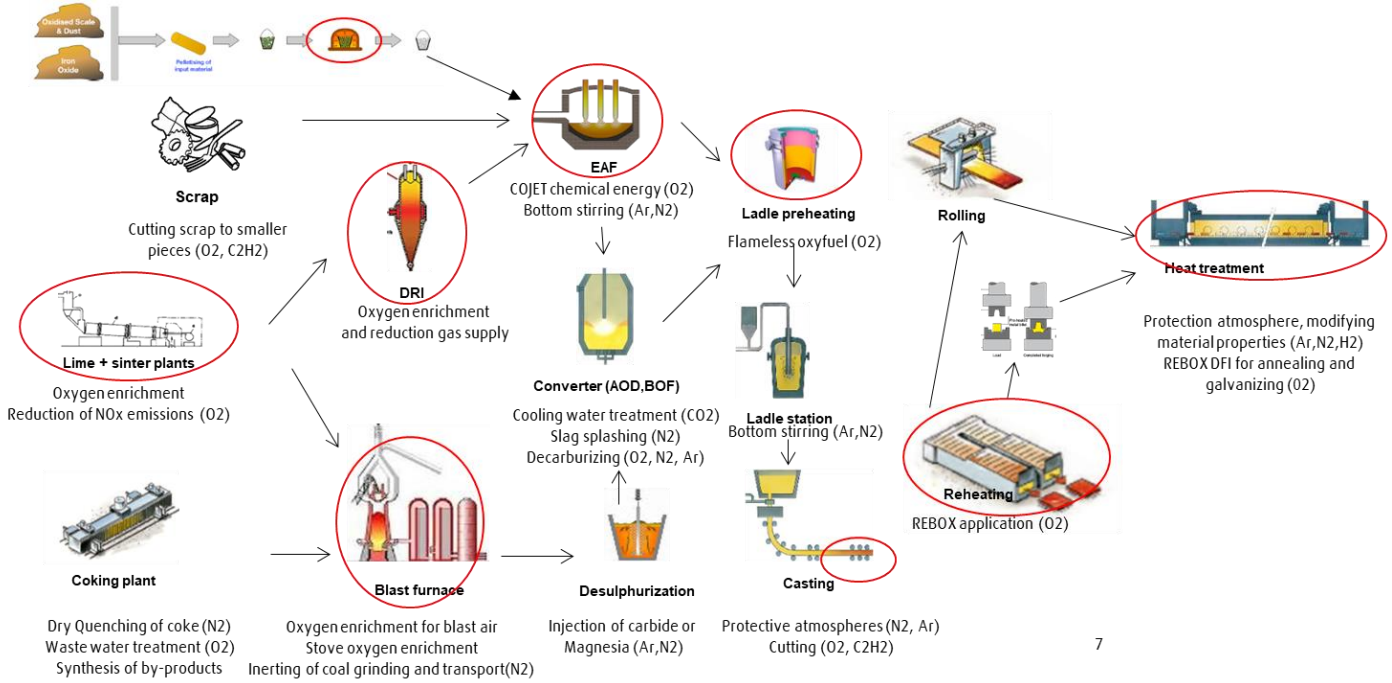
Oxyfuel Combustion:

- Replace current NG-air combustion with O2-H2
- 5-50% fuel saving over air-fuel for the furnace
- Prepares plant for H2 blending / substitution
- Facilitates direct ammonia combustion
- Drives Oxygen Intensity +20-100%
  - Integrated Mill: 150-200 Nm3/t
  - Minimill : 40-55 Nm3/t

Ovako first in the world to heat steel using hydrogen



Linde Oxyfuel Technologies and Hydrogen Applications in a Steel Mill



Summary

1. Substantial growth projected for hydrogen, although timing is uncertain

2. Green hydrogen may not be the only solution. Choice of hydrogen color is dependent on local policy framework and access/price of natural resources

3. PEM electrolysis is the leading technology for green H2 production today. Linde is installing the world largest PEM electrolyzer of 24MW, using 2MW modules. Scale up to 5MW modules and 100+ MW is in development. Scale up and cost reduction are key challenges to be solved.

4. Integration of green H2 and O2 supply into a steel mill, either existing or greenfield, requires careful consideration. Hydrogen use can be optimized by deploying oxyfuel technologies in the steel mill.

5. Steelmakers can initiate stepwise decarbonization *today* with cost-effective, energy efficiency projects. Oxy-fuel combustion is a prime example.