Hydrogen uses in ironmaking

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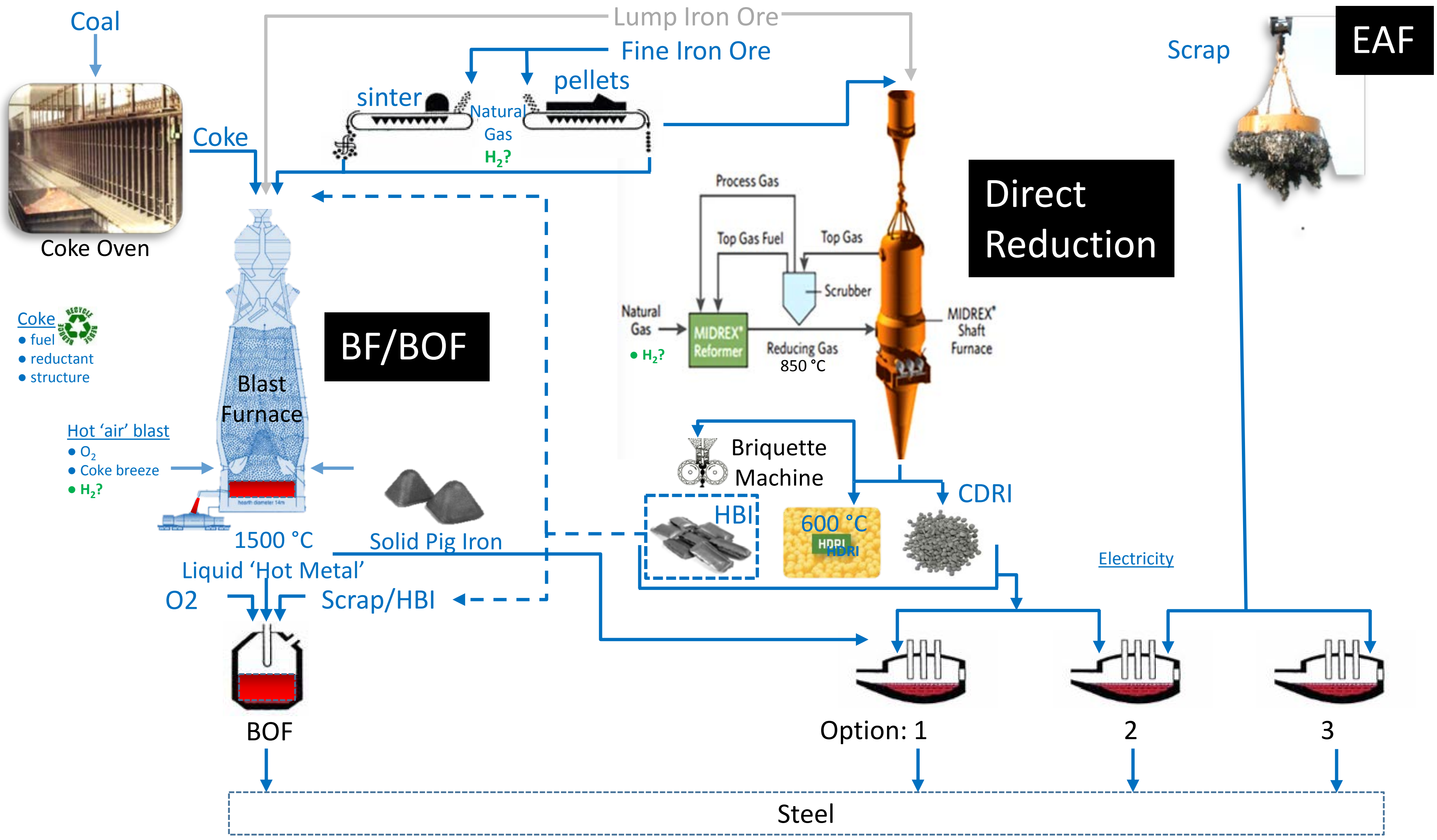
Overview of the steel production process



CO_2 Emissions from steelmaking

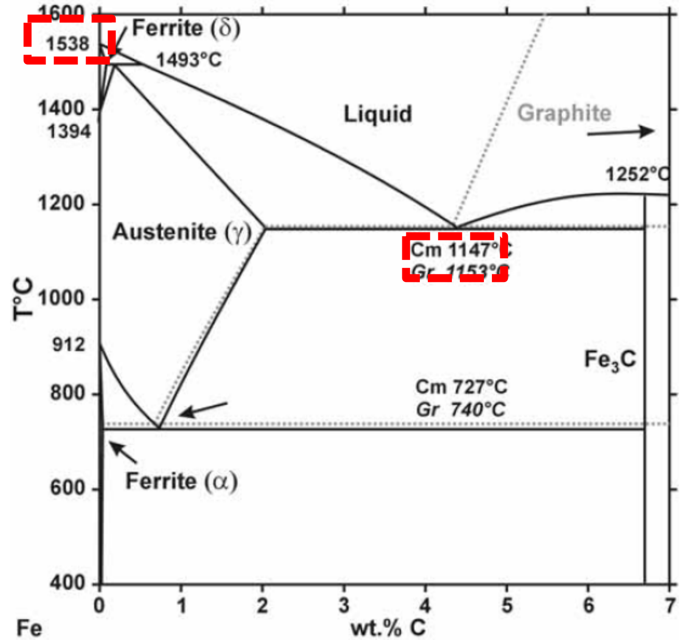
- Steel accounts for 4-5% of the total CO_2 emitted
- Emissions strongly depend on boundary
  - Majority of CO_2 emissions come from power generation, **conversion of iron ore to iron** and re-heating
  - Emissions varies based on how electricity is generated (e.g. coal or nuclear)
- BF-BOF route:
  - 1,600 – 2,000 kg CO_2/ton HRC
  - Limited potential to reduce further (mature technology)
  - Capture / re-use if possible
- EAF (scrap) route :
  - 500-600 kg CO_2 / ton HRC
  - EAF can be misleading: scrap / OBM were previously converted from iron ore
- EAF+DR route:
  - 1,100 – 1,200 kg CO_2 / ton HRC for 100% HDRI charge
  - Lowest commercially proven CO_2 emissions from ore

Carbon in Iron & Steelmaking

Role of carbon in steelmaking:

- Reduces melting point
- Provides energy (with oxygen)
- Steel products contain carbon as alloying element

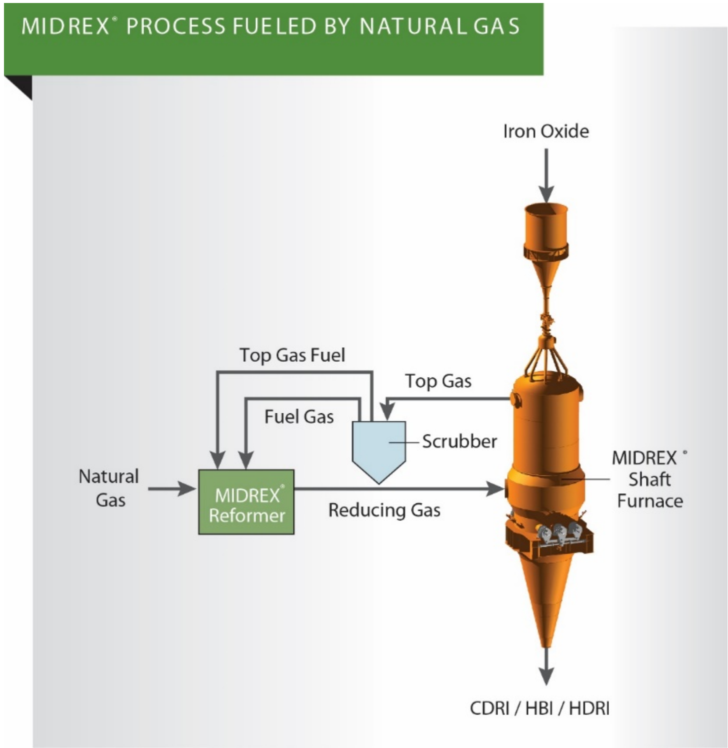
➔ Carbon-free steelmaking is very unlikely but significant reductions in CO_2 emissions can be achieved with H_2



Source: Durand-Charre M. The Microstructure of Superalloys. 1999

Midrex® NG process

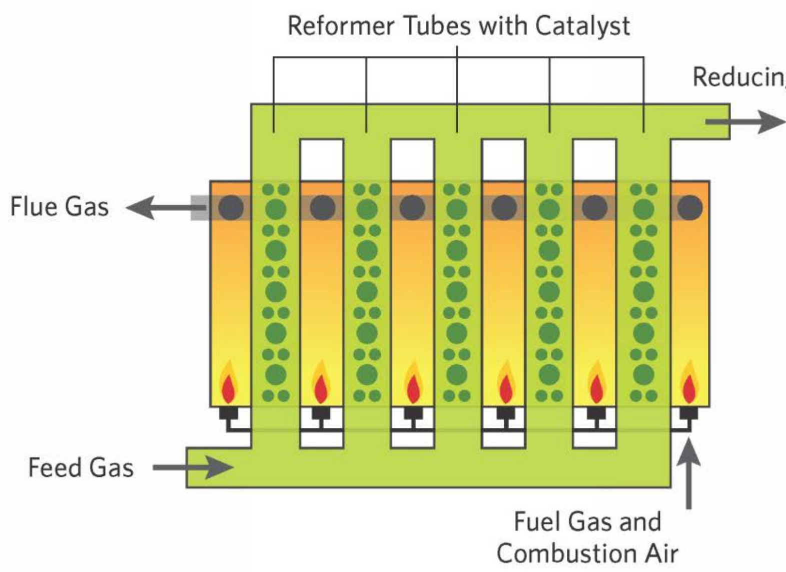
- First plant built in 1969
- Over 70 units constructed worldwide
- Over a **billion tons of iron** produced by the MIDREX® process
- Iron ore is reduced to metallic iron in the MIDREX® Shaft Furnace by **Hydrogen** and CO
- MIDREX Reformer reducing gas composition is typically 55% H_2 and 36%CO (ratio ~1.5)
- Midrex plant with SMR has operated since 1989 ~75% hydrogen



Reactions (w/ Hydrogen only)	Heat	Description
$Fe_2O_3 + 3\ H_2 \leftrightarrow 2\ Fe + 3\ H_2O$	Endothermic	Reduction by H_2
$3\ Fe + CH_4 \leftrightarrow Fe_3C + 2\ H_2$	Endothermic	Carburization
$3\ Fe + CO + H_2 \leftrightarrow Fe_3C + H_2O$	Exothermic	Carburization

Midrex® NG process

- Reducing gases are generated in MIDREX® Reformer.
- Process can use any Natural Gas source regardless of sulfur or heavy hydrocarbon content
- NG consumption ~2.35 Net Gcal / ton DRI



TYPICAL COMPOSITION

	INLET	OUTLET
H_2	35	55
CO	19	35
CO_2	15	2
H_2O	13	6
CH_4	17	1
N_2	1	1
Temp. (°C)	580	980

Reactions (w/ Hydrogen only)	Heat	Description
$CH_4 + CO_2 \leftrightarrow 2CO + 2H_2$	Endothermic	CO_2 reforming
$CH_4 + H_2O \leftrightarrow CO + 3H_2$	Endothermic	H_2O reforming
$CH_4 \leftrightarrow C + 2H_2$	Endothermic	Methane cracking
$CO + H_2 \leftrightarrow C + H_2O$	Exothermic	Beggs or Water/carbon shift
$CO + H_2O \leftrightarrow CO_2 + H_2$	Exothermic	Water/gas shift

Newest MIDREX® Plants in North America

Voestalpine (Corpus Christi, Texas USA)

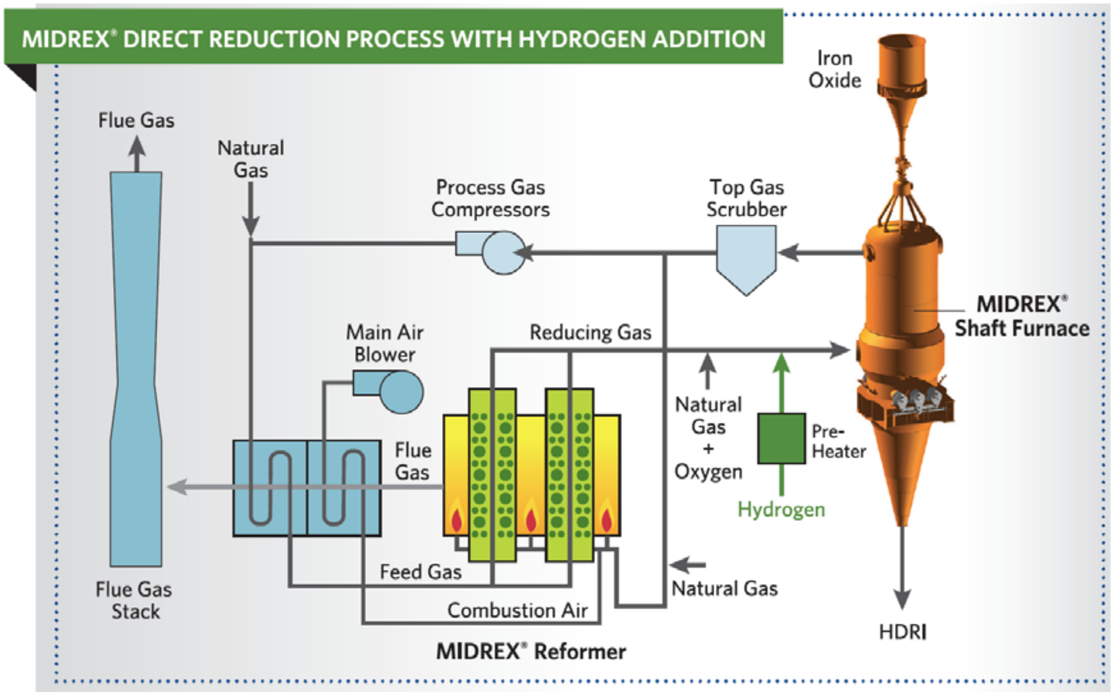
- 2.0 MTPA HBI
- Performance test passed February 19, 2017

Cleveland-Cliffs (Toledo, OH USA)

- 1.6 MTPA HBI
- Completion: 2020

MIDREX® NG with H_2

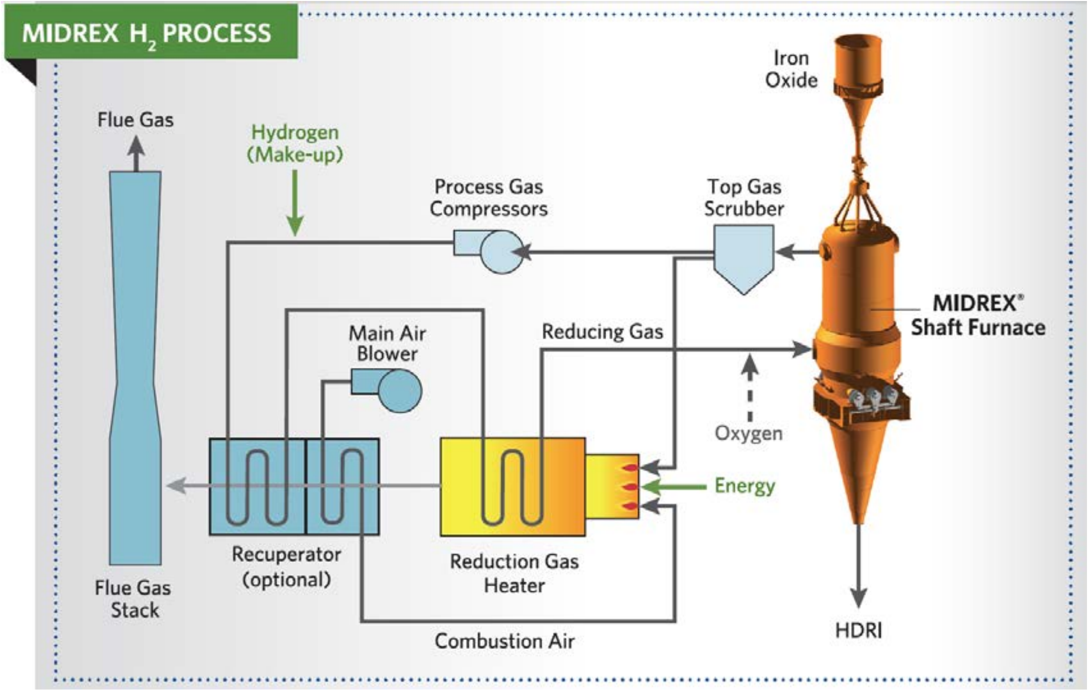
- Up to 30% of NG can be substituted by Hydrogen without changing the process
- Hydrogen may need to be pre-heated depending on quantities added
- Rough calculations for Cleveland- Cliffs:
  1.6 MTPA (200 ton/h), up to 16,000Nm^3/h of NG* can be replaced by 48,000Nm^3/h of H_2
- Hydrogen can be increased in the process as it becomes available



* Assumes net heating value 8800 kcal/Nm^3

MIDREX® H_2™

- Bustle gas composition is ~90% hydrogen, balance CO, CO_2, H_2O and CH_4 (for 1.4% carbon in DRI)
- Hydrogen consumption is approx. 650 Nm^3/t DRI (54kg/t)
- For a Midrex plant the size of Cleveland-Cliffs, that's approx. **130,000Nm^3/h of H_2**
- ~650MW per Midrex plant (at 200Nm^3/h of H_2 per 1MW)



Conclusions

- MIDREX-NG® is a proven technology for industrial production of iron, using "fossil" hydrogen at scale. The process can reduce CO_2 emissions by 50%-80% over traditional BF-BOF.
- Direct reduction can be a bridge technology for ironmaking as Hydrogen becomes available at scale
  - New plants can be built or existing plants can be converted to 100% H_2 as the Hydrogen economy evolves
- Green hydrogen production volumes need to increase by 50x – 125x to supply one MIDREX® plant
  - Scale up to Demonstration plant will be needed
- Hydrogen production costs must be competitive: steelmaking is a very competitive business with small margins
- European steelmakers are very active