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1944 - 2019 75 YEARS OF INNOVATION

Decarbonising H_2 for DRI Feed

CIE

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Introduction

- The steel industry contributes ~7-9% of the worlds CO_2 emissions
- To meet emissions targets by 2050 the steel industry will need to change their production methods
- Efficiencies can be made across the industry and processes to reduce energy and carbon usage
- Energy efficiencies alone will not achieve the 80% reduction required
- Large amounts of fossil fuels are consumed to produce steel, if these could be replaced then significant reduction in emissions could be achieved
- An option for fossil fuel replacement is hydrogen as a fuel and as a reductant
- There are many routes for the production of hydrogen
- Has the hydrogen revolution began?

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Predicted steel and emissions constraints

Compared to emissions levels in 2015, for the steel industry to meet required emissions targets, a relative reduction of 90% will be required by 2050

To form part of the solution direct reduced iron (DRI) and electric arc furnaces (EAF) will be integral

The use of increased percentages of scrap steel will be essential to achieve these targets

Material Economics. The Circular Economy—A Powerful Force for Climate Mitigation. Available online: https://www.climate-kic.org/insights/the-circular-economy-a-powerful-force-for-climate-mitigation-2/ (accessed on 18 April 2021).

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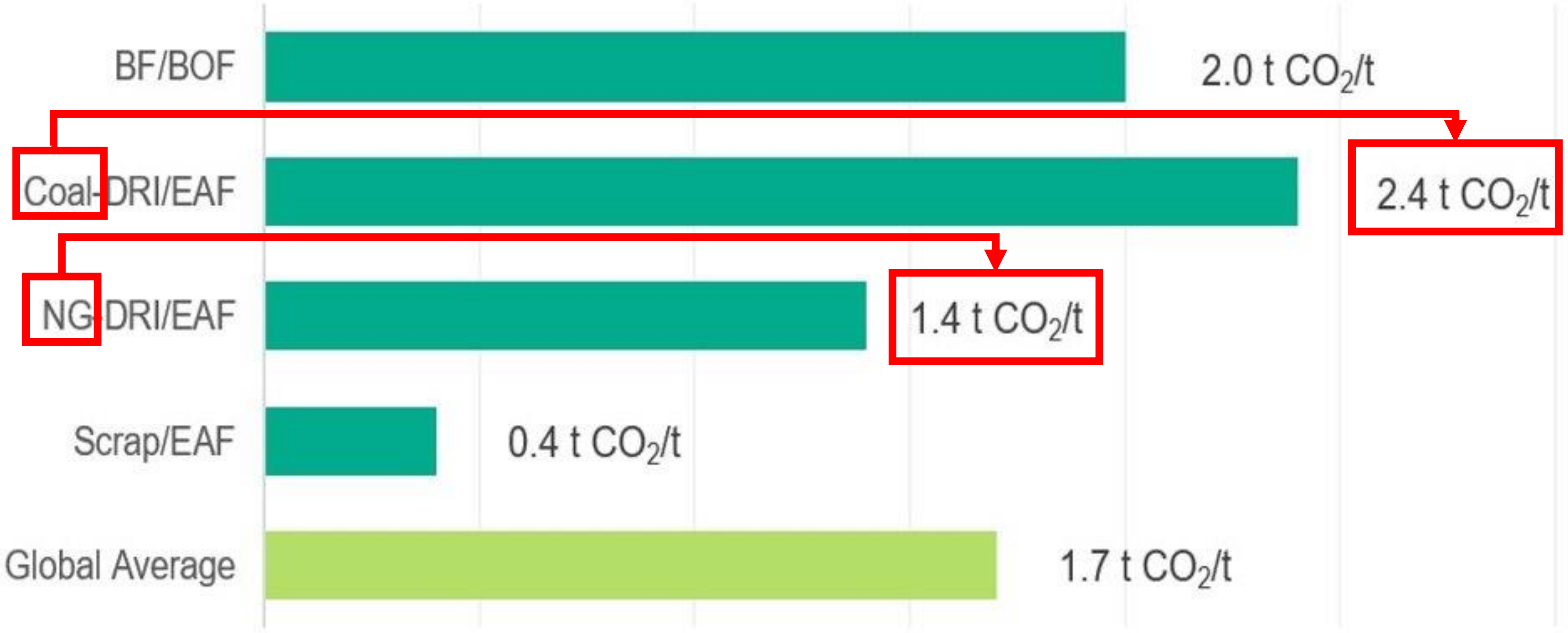
Emissions factors for steel production



Emissions figures for routes of steel production

DRI/EAF can show significant reduction in emissions figures, however when coal is used as a fuel source the emissions can be higher than the integrated steel route

Using natural gas (NG) reduces emissions to 1.4 tCO_2/t

The use of scrap only can yield reductions as low as 0.4 tCO_2/t

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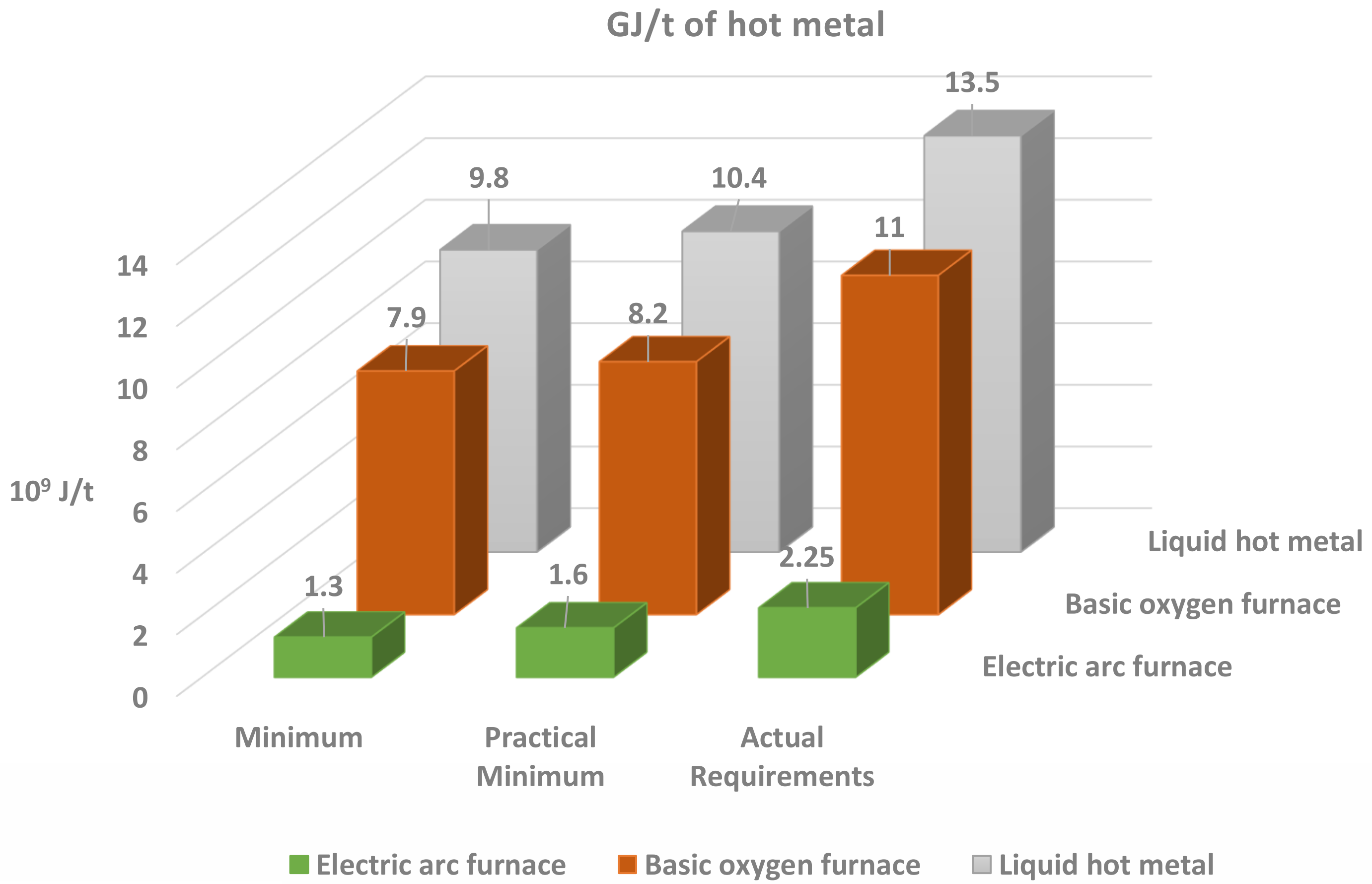
Energy demand per tonne of hot metal



Steel industry has reduced energy consumption by 50% over the last 30 years

DRI uses ~10.4GJ/t of reduced iron

A move to more EAF steel production will lead to a greater dependency on electricity as a primary energy source

Electricity is more expensive than gas or coal as an energy source

A guaranteed consistent supply of electricity is required that does not impinge on society)

29% of Global steel from EAF, therefore = 1.17EJ/yr (actual requirements)

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Introduction to H_2 across the EU

- Across the EU, there is recognition that hydrogen can form part of the future energy mix
- The installation of 6GW of electrolysers by 2024 will produce up to 1Mt of H_2
- By 2030, up to 10 Mt of renewable H_2 is forecast to be produced
- Large scale deployment of renewable H_2 across all industry is anticipated
- At these scales there is potential for significant reduction in the use of fossil fuels

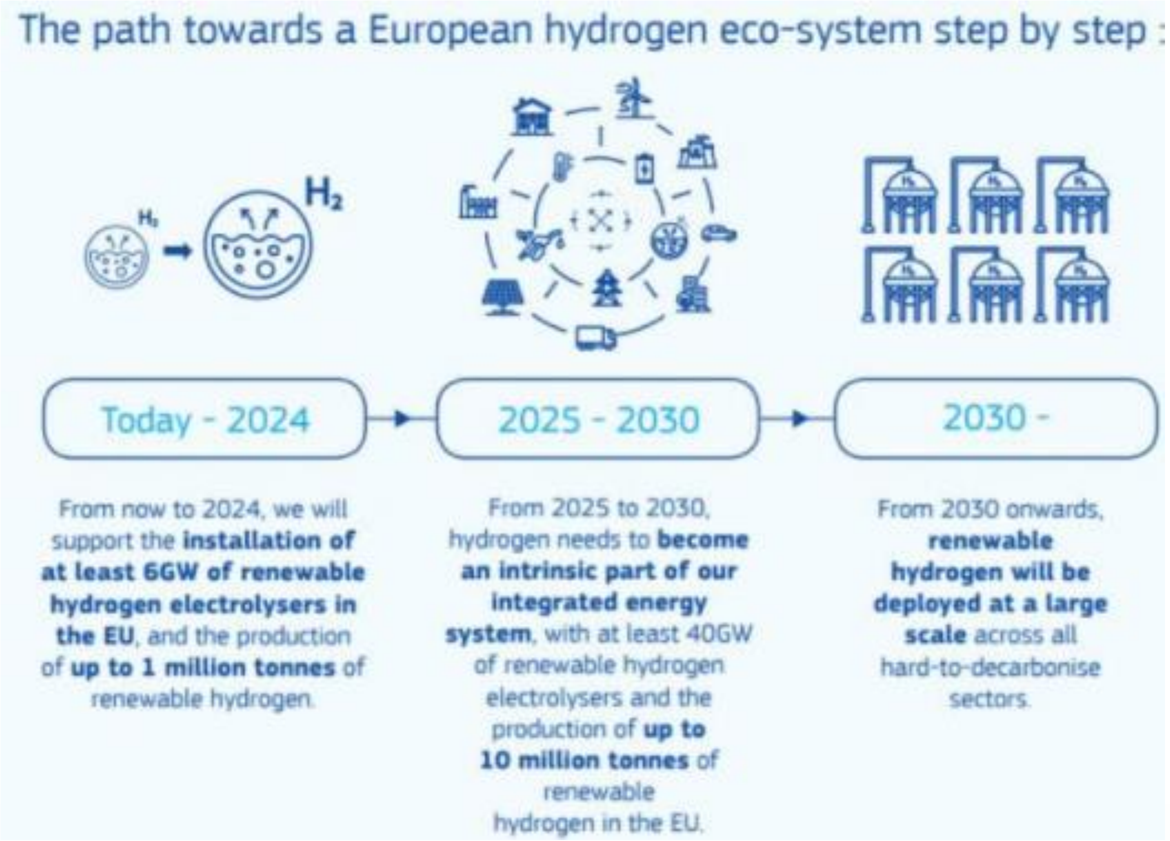

Image courtesy EU Commission

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Early 2020s (2022-2024)

Hydrogen economy 'archetype'

Production
Small-scale electrolytic production

Networks
Direct pipeline, co-location, trucked (non-pipeline) or onsite use

Use
Some transport (buses, early HGV, rail & aviation trials); industry demonstrations; neighbourhood heat trial

Key actions and milestones

- Launch NZHF early 2022
- Phase 1 CCUS cluster decision 2021
- Finalise low carbon hydrogen standard 2022
- Finalise business model 2022
- Heat neighbourhood trial 2023
- Value for money case for blending Q3 2022

Mid-2020s (2025-2027)

Production
Large-scale CCUS-enabled production in at least one location; electrolytic production increasing in scale

CO_2

Networks
Dedicated small-scale cluster pipeline network; expanded trucking & small-scale storage

Use
Industry applications; transport (HGV, rail & shipping trials) village heat trial; blending (tbc)

- Aiming for 1GW production capacity 2025
- At least 2 CCUS clusters by 2025
- Heat village trial 2025
- Hydrogen heating decision by 2026
- Decision on HGVs mid-2020s

Late 2020s (2028-30)

Production
Several large-scale CCUS-enabled projects & several large-scale electrolytic projects

CO_2

Networks
Large cluster networks; large-scale storage; integration with gas networks

H_2

Use
Wide use in industry; power generation & flexibility; transport (HGVs, shipping); heat pilot town (tbc)

- Ambition for 5GW production capacity 2030
- 4 CCUS clusters by 2030
- Potential pilot hydrogen town by 2030
- Ambition for 40GW offshore wind by 2030

Mid-2030s onward

Production
Increasing scale & range of production – e.g. nuclear, biomass

CO_2

Networks
Regional or national networks & large-scale storage integrated with CCUS, gas & electricity networks

H_2

Use
Full range of end users incl. steel; power system; greater shipping & aviation; potential gas grid conversion

- Sixth Carbon Budget

Source: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1011283/UK-Hydrogen-Strategy_web.pdf

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Production of H_2 for the steel industry

- Global production of steel is ~1.80 Bn tonnes
- Steel produced through the Direct Reduction Furnace (DRI) and Electric Arc Furnace (EAF) route equates to 108 M tonnes/yr
- The emissions from the electric route of steel making is already lower than from the integrated route ~ 0.6 tCO_{2eq}/tHM compared to 1.8 tCO_{2eq}/ tHM
- The electric process still utilises large quantities of fossil fuels, in the form of natural gas and some hard carbon
- The natural gas may be able to be substituted with hydrogen as a reductant
- The production of H_2 as a fuel from electricity may not be cost effective, as heating could be provided direct from the electricity supply, (unless there is some chemical or reactive benefit to the use of H_2)

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Methods of H_2 production

- Methane steam reforming
  - Natural gas
  - Methane
- Autothermal reforming (ATR)
- Gasification
  - Coal
  - Biomass
- Pyrolysis
- Electrolysis
  - Conventional electricity
  - Renewable power

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Steam reforming

- Traditional steam reforming processes fossil fuels using steam to produce a stream of H_2,
- Carbon dioxide and methane are combined to produce syngas

$$CH_4 + CO_2 \rightarrow 2CO + \boxed{2H_2}$$

$$CH_4 + H_2O \rightarrow CO + \boxed{3H_2}$$

- These reactions are endothermic requiring 206 kJ/mol
- The carbon monoxide can be further reacted with water, in the water gas shift reaction to produce carbon dioxide and hydrogen

$$CO + H_2O \rightarrow CO_2 + \boxed{H_2}$$

- The water gas shift reaction is exothermic releasing 41 kJ/mol, therefore some energy recovery is possible from the process
- Processed sustainable biomasses may provide a renewable alternative to fossil fuel steam reforming

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Autothermal reforming

- ATR is an alternative method of H_2 production through steam reforming
- ATR uses elevated levels of O_2 (compared to steam reforming)
- ATR produces syngas and water
- The water can be used in the second reaction to produce further H_2, and again in a water gas shift reactor

$$2CH_4 + O_2 + CO_2 \rightarrow \boxed{3H_2} + 3CO + H_2O$$

$$4CH_4 + O_2 + 2H_2O \rightarrow \boxed{10H_2} + 4CO$$

- The oxidation process is exothermic, releasing heat as a by-product, whilst the syngas leaves the reactor at 950-1100°C
- With both steam reforming and autothermal reforming, the use of CCS may provide a method of reducing emissions from these processes

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Gasification

Gasification can be carried out on several feedstocks:

- Biomass
- Domestic, agricultural and commercial food wastes
- Fossil fuels

Syngas is the desired product

Secondary products include

- Tars
- Charcoal
- Chars
- Heat
- Lignin (from biomass)

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Biomass Gasification

Feedstock →	Drying 100-150°C	Pyrolysis 200-500°C	Oxidation 800-1200°C	Reduction 650-900°C
	Removal of moisture, some loss of lower volatiles	Heating without air to release volatiles and produce biochar	Addition of air and O_2 for oxidation and combustion	Conversion of remaining product to producer gas
	Endothermic	Endothermic	Exothermic	Endothermic
	H_2O	$C_6H_{10}O_5 \rightarrow 5CO + 3H_2 + CH_4$ $C_6H_{10}O_5 \rightarrow 5CO + 5H_2 + C$ $C_6H_{10}O_5 + 1/2O_2 \rightarrow 6CO + 5H_2$	$C_6H_{10}O_5 + O_2 \rightarrow 5CO + 5H_2 + CO_2$ $C_6H_{10}O_5 + O_2 \rightarrow 3CO + 5H_2 + 3CO_2$	$C_6H_{10}O_5 + H_2O_2 \rightarrow 6CO + 16H_2$ $C_6H_{10}O_5 + 3H_2O_2 \rightarrow 4CO + 8H_2 + 2CO_2$ $C_6H_{10}O_5 + O_2 \rightarrow 3CO + 5H_2$

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Hydrogen water electrolysis

- Electrolysis is a process of electrochemically separating out the constituent parts of water
  - H_2
  - O_2
- For electrolysis to be “green”, the electricity needs to come from a renewable and sustainable source
- The use of hydro-electricity, may be an option, however this source provides a base load of power in many countries
- The use of off peak wind and solar may be viable options as an electricity supply for the production of hydrogen, providing a cheaper and effective method of production
- Whilst we only consider electrolysis for H_2 production, the secondary product of O_2 is a highly valuable commodity and if handles correctly could be considered a second revenue stream

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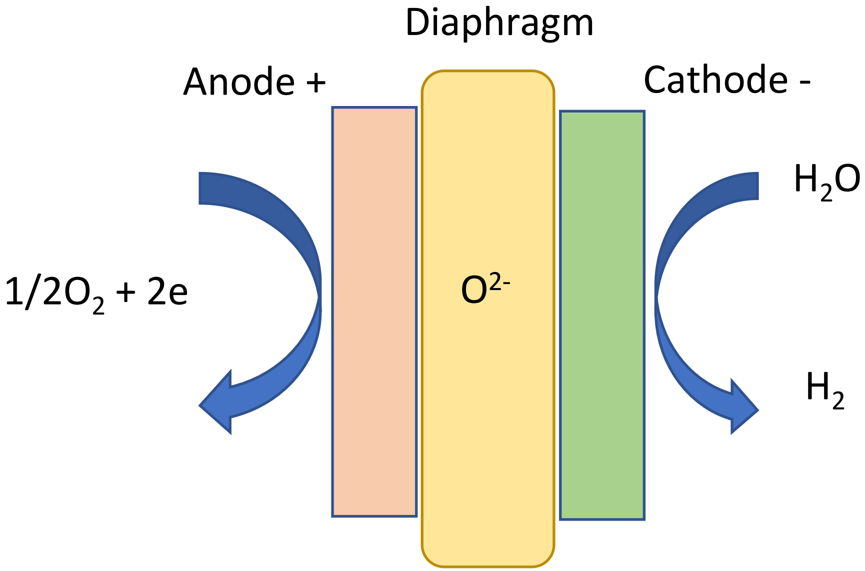
Solid Oxide electrolysis (SOE)

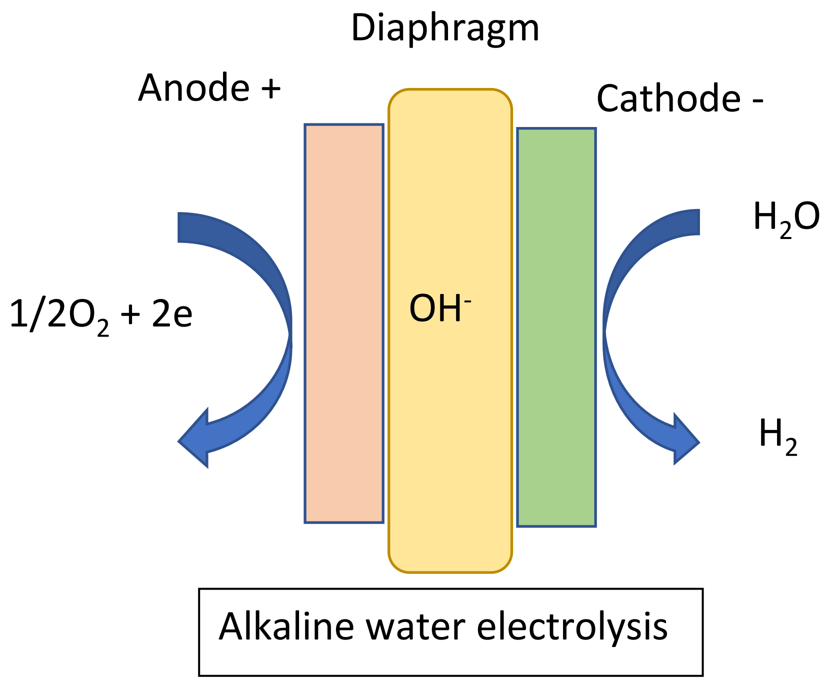
- SOE produces H_2 at the cathode from water, with O_2 passing through the diaphragm and being released at the anode
- The system operates at high pressures and temperatures of 1000°C
- Some laboratory scale equipment is operating at lower temperatures of 500-850°C
- Efficiencies have been recorded at 90-100%



Solid oxide electrolysis

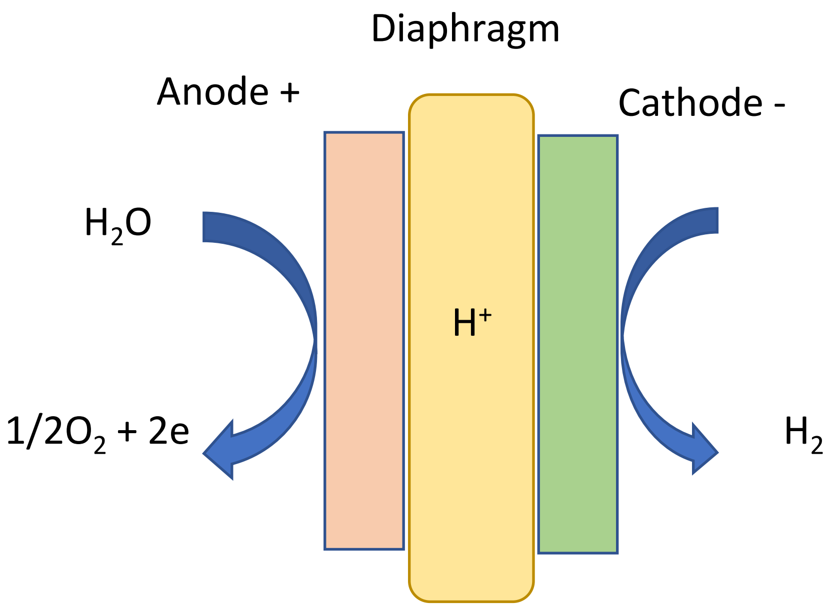
Alkaline water electrolysis (AWE)

- AWE is a well established technology operating at temperatures of 30-80°C
- Equipment in the MW range are in operation
- Alkaline solutions of KOH and NaOH are used
- H_2 is produced at the cathode from water
- Hydroxyl is passed through the diaphragm
- O_2 is produced at the anode from the hydroxyl
- AWE systems are in operation at 70-80% efficiency



Polymer electrolyte membrane (PEM)

- PEM are an established system and can be used for electricity production as fuel cells if the hydrogen is of a pure grade
- PEM have typical efficiencies of 80-90%
- Purity of product 99.99%
- Water is separated at the anode, where O_2 is released
- Hydrogen ions pass through the diaphragm
- H_2 is released at the cathode
- Electrons are produced during the process, which can be used to partially supply power for the operation



Polymer electrolyte membrane

Advantages and disadvantages of electrolysis systems

Process	Advantages	Disadvantages
PEM	High efficiency, 80-90% High purity product 99.99%	New technology Low durability High costs
AWE	Established technology Energy efficiency 70-80% Non noble catalysts	Low current density Low purity of product
SOE	High efficiency 90-100% Non noble catalyst at high operating pressure	Laboratory scale only with low durability

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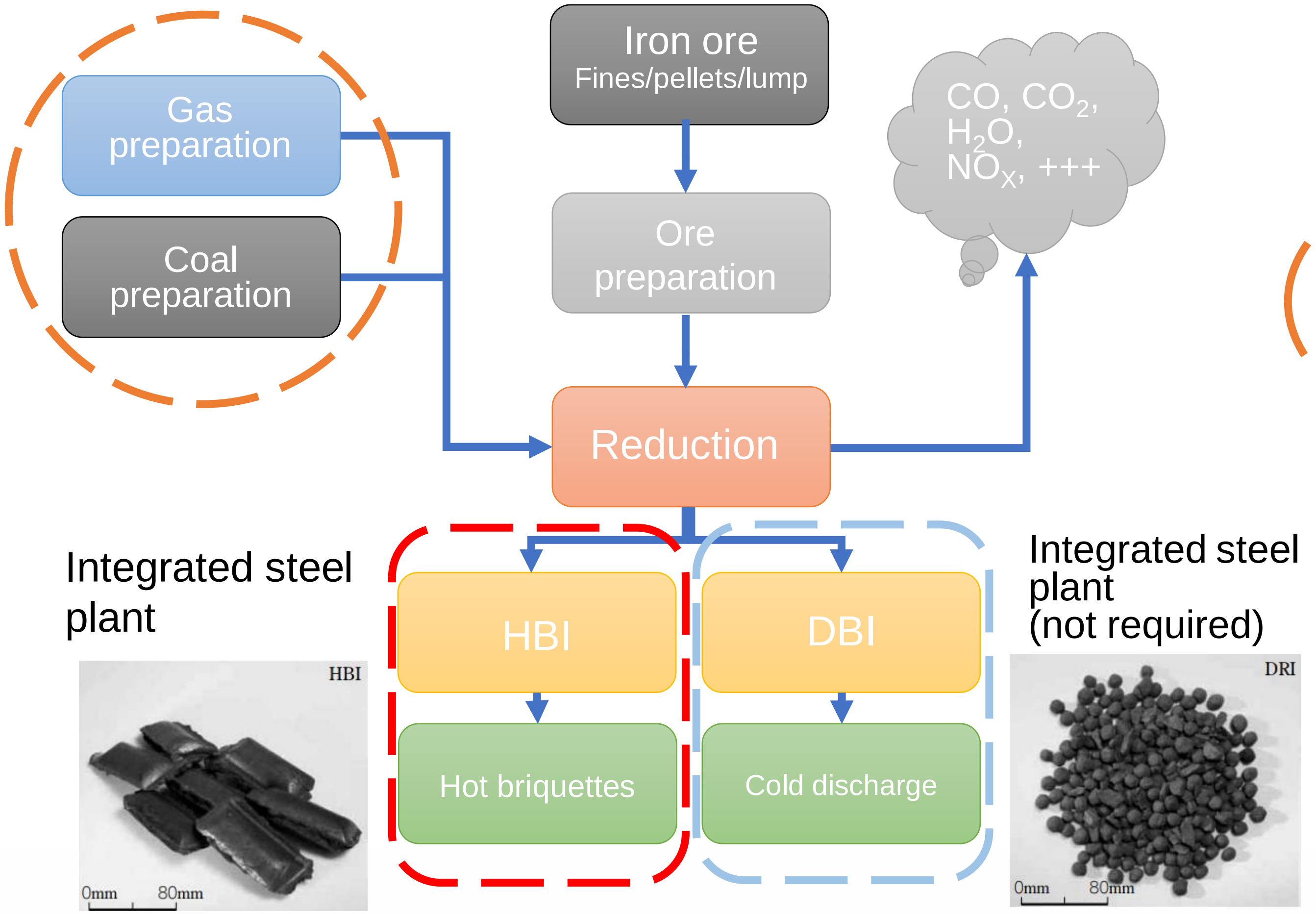
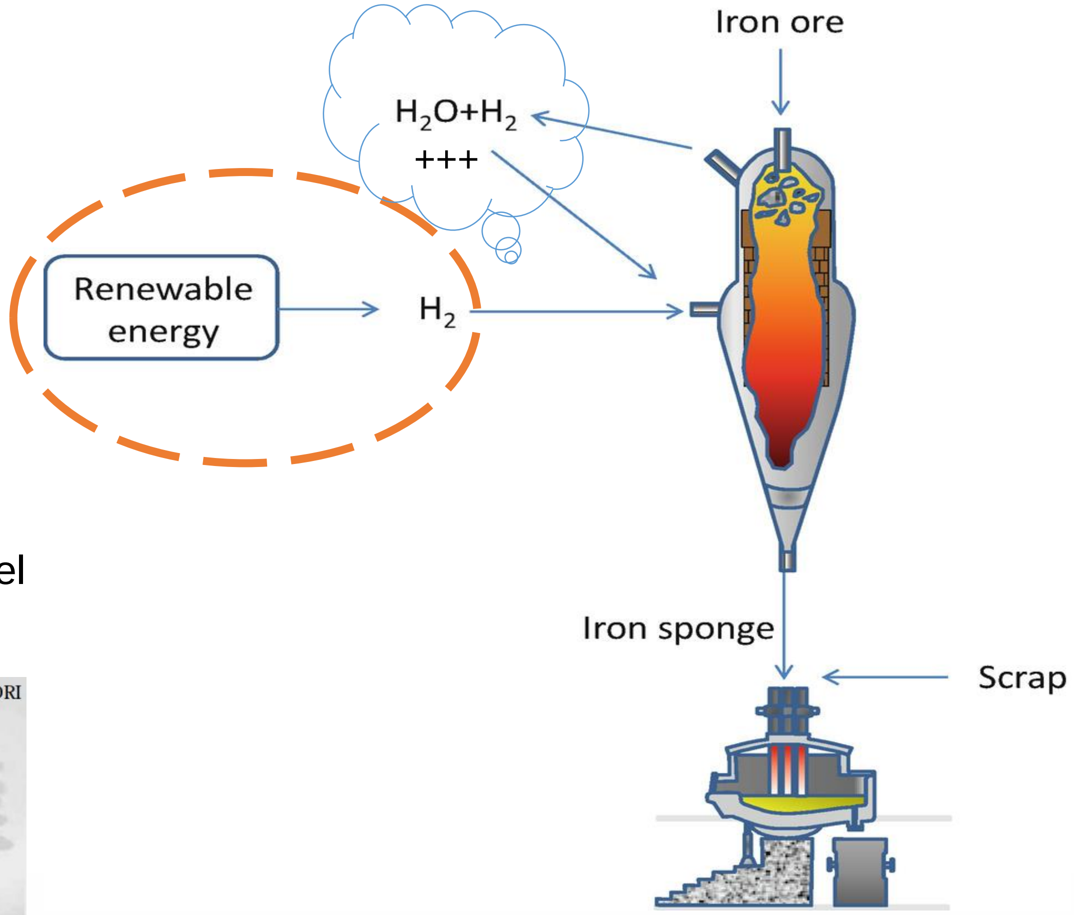
Direct reduction process





Adapted from Cavaliere P. (2019) Direct Reduced Iron: Most Efficient Technologies for Greenhouse Emissions Abatement. In: Clean Ironmaking and Steelmaking Processes. Springer, Cham. https://doi.org/10.1007/978-3-030-21209-4_8

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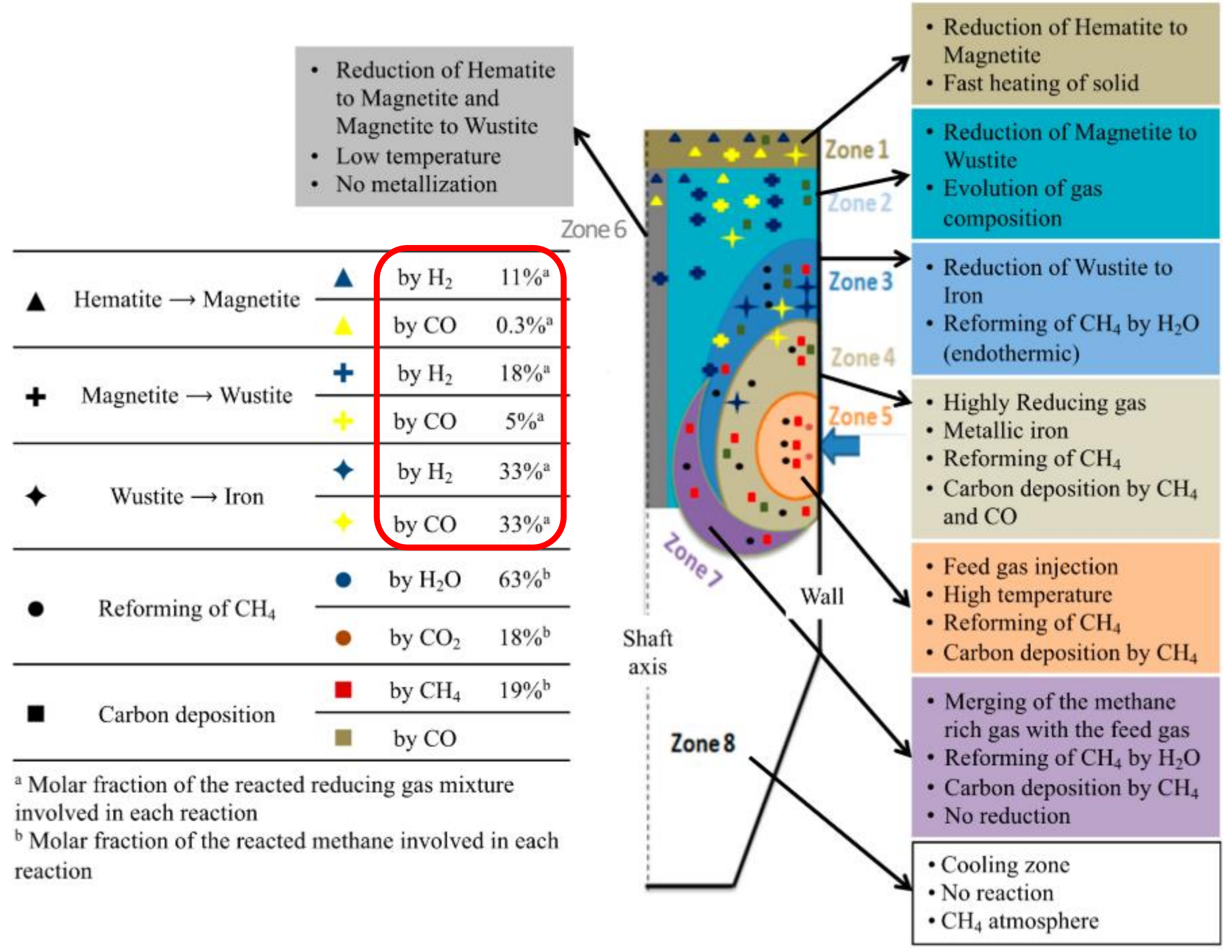
Reaction pathways in a DRI from syngas

- From the reactions shown in the figure, when syngas is used hydrogen plays a significant part of the process as a reductant along with carbon monoxide
- During the hematite to magnetite phase, only 11% of the reduction is by H_2
- The magnetite to wüstite, 18% of H_2 is effective as a reductant
- Finally, wüstite to iron sees 33% of the H_2 acting as a reductant
- Total of 62% reduction by H_2
- Indirect reduction of FeO with CO is exothermic
- FeO reduction by H_2 is endothermic



Hamadeh, H.; Mirgaux, O.; Patisson, F. Detailed Modeling of the Direct Reduction of Iron Ore in a Shaft Furnace. *Materials* **2018**, *11*, 1865. https://doi.org/10.3390/ma11101865

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Summary

- Hydrogen can be used as part of the energy mix and reduction/reactants for significantly reducing the emissions from the steel industry, particularly as a reductant in the electrical steel route
- There are many systems for hydrogen production
  - Steam reforming
  - Autothermal reforming
  - Gasification
  - Electrolysis
- To produce hydrogen with reduced carbon emissions, some systems will need to deploy CCUS is they are to continue using fossil fuels
- Electrolysis can produce H_2 with minimal carbon emissions if the electricity is provided from renewable and sustainable sources
- There is no one solution to fit all decarbonisation, however electrolysis may provide a viable option for the steel industry to become compliant with future emissions regulations

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Thank you

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