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Low-carbon, blue hydrogen
High-potential, low-cost

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gasworld EMEA conference

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Introduction

Stephen B. Harrison is the founder and managing director at sbh4 GmbH in Germany. His work focuses on decarbonisation and greenhouse gas emissions control. Hydrogen and CCUS are fundamental pillars of his consulting practice.

With a background in industrial and specialty gases, including 27 years at BOC Gases, The BOC Group and Linde Gas, Stephen has intimate knowledge of hydrogen and carbon dioxide from commercial, technical, operational and safety perspectives. For 14 years, he was a global business leader in these FTSE100 and DAX30 companies.

Stephen has extensive buy-side and sell-side M&A due diligence experience in the energy and clean-tech sectors. Private Equity firms and investment fund managers are regular clients. He is also the international hydrogen expert and team leader for an ADB project related to renewable hydrogen deployment in Pakistan.

As a member of the H2 View and **gas**world editorial advisory boards, Stephen advises the direction for these international publications. He is also a member of the scientific committees for AQE 2021 and CEM 2023, leading international conferences for continuous emissions monitoring and air quality.

Hydrogen can support decarbonisation of heavy industry, but hydrogen production generates CO_2

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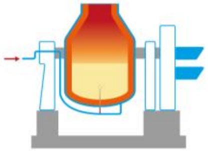
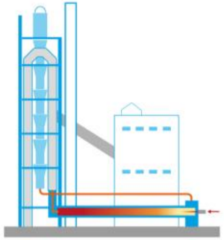
Notes:

- CO_2 emissions are also associated with the energy and power requirements for this industry sector – the focus in this table is CO_2 emissions from within the process
- CCS to capture CO_2 from the process and / or the associated energy production is possible

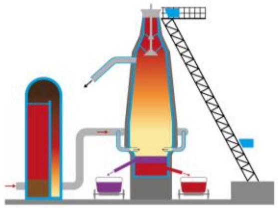
Steam Methane Reformer



Aluminium smelting



Calciner tower & clinker kiln



Blast furnace

	Oil refining	Aluminium smelting	Cement making	Iron making
Application that releases CO_2	Hydrogen production from methane reforming for fuels desulphurisation	Reduction of alumina to aluminium using graphite electrodes	Reduction of limestone to calcium oxide	Reduction of iron ore to iron using coke
Chemical reaction producing CO_2	$CH_4 + H_2O \rightarrow CO + 3H_2$ $CO + H_2O \rightarrow CO_2 + H_2$	$2Al_2O_3 + 3C \rightarrow 4Al + 3CO_2$	$CaCO_3 \rightarrow CaO + CO_2$	$2Fe_2O_3 + 3C \rightarrow 4Fe + 3CO_2$ $Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2$
Decarbonisation approach	Use turquoise hydrogen or green hydrogen to avoid the reforming reaction; or feed the reformer with biomethane instead of natural gas	Use carbon from turquoise hydrogen production instead of carbon from fossil fuels to make the electrodes	Replace a portion of the limestone with alternative materials such as calcined clay to make clinker for cement	Use turquoise hydrogen or green hydrogen instead of coke; or substitute coke with carbon from turquoise hydrogen production
Reactions for the decarbonised process	As above using renewable methane	As above using renewable graphite electrodes	Above reaction can only partially be avoided	As above using renewable carbon, or use hydrogen: $Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O$
Other industries with similar applications	Ammonia, Urea, Methanol, Gas-to-liquids	Gold and silver refining, electric arc furnace to melt scrap steel	Lime making Refractory bricks, $MgCO_3 \rightarrow MgO + CO_2$	None

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Low-carbon hydrogen: a rainbow of colours

Blue – natural gas reforming with CCS

Turquoise – methane pyrolysis with solid carbon

Purple – coal or petcoke gasification with CCS

Pink – electrolysis using nuclear power

Green – electrolysis using renewable power or biomethane reforming

These colours are used for this presentation, other speakers may use other definitions. There is no international standard.
Black or brown hydrogen from coal or petcoke gasification and grey hydrogen from natural gas reforming are dominant in the world today – both have a significant carbon dioxide emissions footprints.

The "blue-bridge“ - 27 Jan 2021 MEP's voted that blue hydrogen can be a bridge to green

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How green is blue?
An update from 21 April 2021

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3.10. Manufacture of hydrogen

Description of the activity

Manufacture of hydrogen and hydrogen-based synthetic fuels.

Where the CO_2 that would otherwise be emitted from the manufacturing process is captured for the purpose of underground storage, the CO_2 is transported and stored underground, in accordance with the technical screening criteria set out in Sections 5.11 and 5.12, respectively, of this Annex.

- Extract from Annex 1 of latest draft of the EU Taxonomy regulations
- Define sustainable investment, related to the Renewable Energy Directive
- Sections 5.11 and 5.12 refer to captured CO2 transportation and permanent underground storage

https://ec.europa.eu/info/business-economy-euro/banking-and-finance/sustainable-finance/eu-taxonomy-sustainable-activities_en

Blue hydrogen production consumes methane gas on a reformer followed by CCS

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Methane reforming, pyrolysis, gasification and combustion

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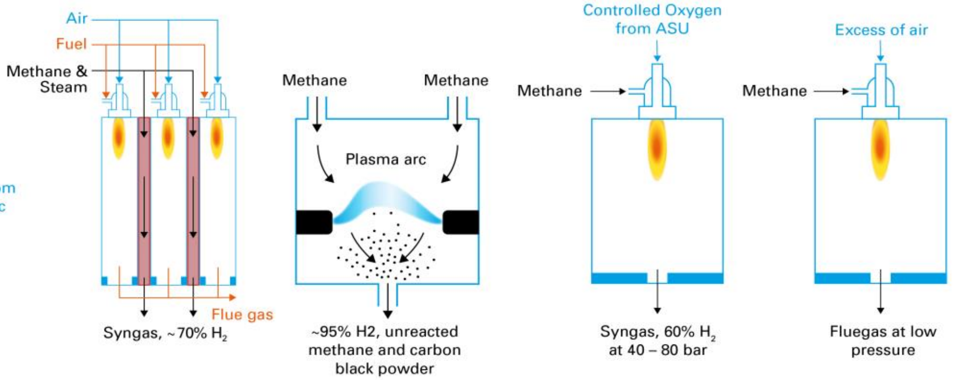
Notes:
- Energy for pyrolysis may be from combustion of fuel, or from an electric plasma arc
- Pyrolysis diagram shown is for thermal plasma pyrolysis
- POX diagram shows non-catalytic POX



Process	Steam Methane Reforming	Methane Pyrolysis (Methane splitting or cracking)	Methane Partial Oxidation – POX (Gasification)	Methane Combustion (Thermal oxidation)
Oxygen feedstock	Oxygen is supplied as part of the water molecule with the steam	None, oxygen-free process	Oxygen from ASU	Air fed in excess
Catalyst required	Yes, generally Nickel	No	Not for thermal POX	No
Energy required/released	Endothermic, requires heat input	Endothermic, requires heat input	Exothermic, steam generation	Exothermic, steam generation
Chemical reaction	$CH_4 + H_2O \rightarrow CO + 3H_2$	$CH_4 \rightarrow C + 2H_2$	$2CH_4 + O_2 \rightarrow 2CO + 4H_2$ (ideal case)	$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$ (ideal case)
Carbon product	CO and CO_2	Carbon black powder	CO and CO_2 from side reactions	CO_2
Hydrogen content in product gas	~70%	~95%	~60%	Zero, complete oxidation to CO_2 & H_2O is ideal case
Product gas pressure	15 to 40 bar	Atmospheric pressure	40 to 80 bar	Atmospheric pressure
Product gas temperature	~850 °C	~1700 °C	~1400 °C	~1400 °C

ATR and POX technologies require an ASU to supply oxygen

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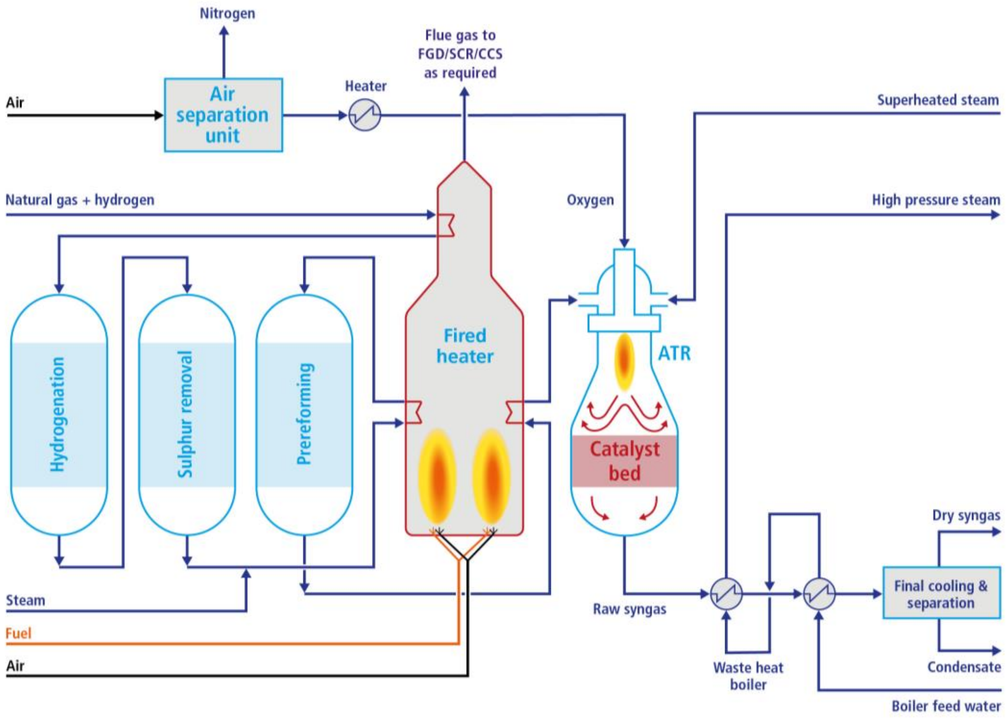

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ATR hydrogen with integrated ammonia production to use nitrogen from the ASU

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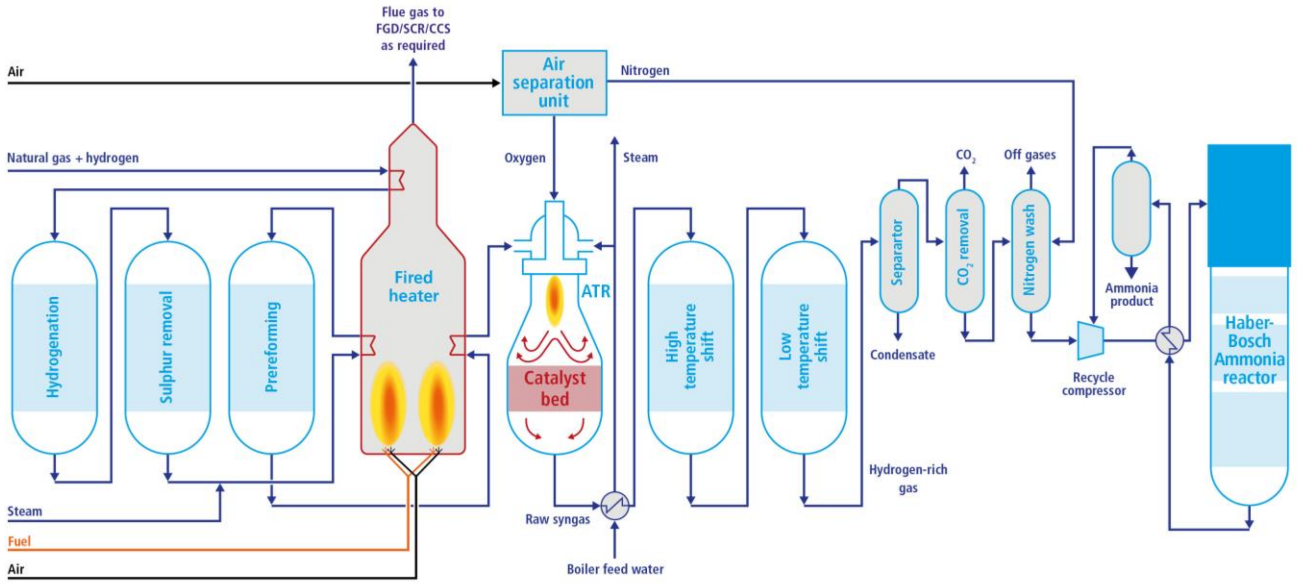

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Petra Nova coal-fired power generation, post-combustion CCUS. Demonstration plant from Dec 2016 to Aug 2020

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The wisdom of humour

Passenger: “Do you know the way to the post office?”

Driver: “If I were going to the Post Office, I would not start here!”

Electrical heating avoids post-combustion CCS

Process development at Nu:ionic in Canada has demonstrated that microwave catalytic reforming is highly effective…

- Significantly smaller reactor volume
- 25 to 30% less natural gas consumption
- CCS only required on the CO_2-rich process gas
- Catalyst coking is reduced (and can be reversed)
- Catalyst is more tolerant of sulphur traces in the feedstock
- Similar technology is being tested for dry methane reforming and ammonia production

Dielectric Microwave Catalytic Steam Methane Reforming (µSMR)

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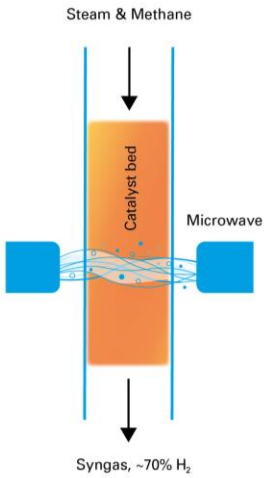
Notes:
- Microwave plasma would be an alternative to dielectric microwave heating and would allow lower exit gas temperature



Process	Dielectric Microwave Catalytic Steam Methane Reforming (µSMR)
Carbon feedstock	Methane from natural gas or biomethane
Target chemical reactions	$CH_4 + H_2O \rightarrow CO + 3H_2$
Additional side reactions	$CO + H_2O \rightarrow CO_2 + H_2$
Carbon produced as	CO and CO_2
Hydrogen content in product gas	~70%
Product gas pressure	10 to 40 bar
Product gas temperature	500 °C to 850 °C

Cost benchmarking – electrolysis, blue and grey hydrogen (excludes distribution costs)

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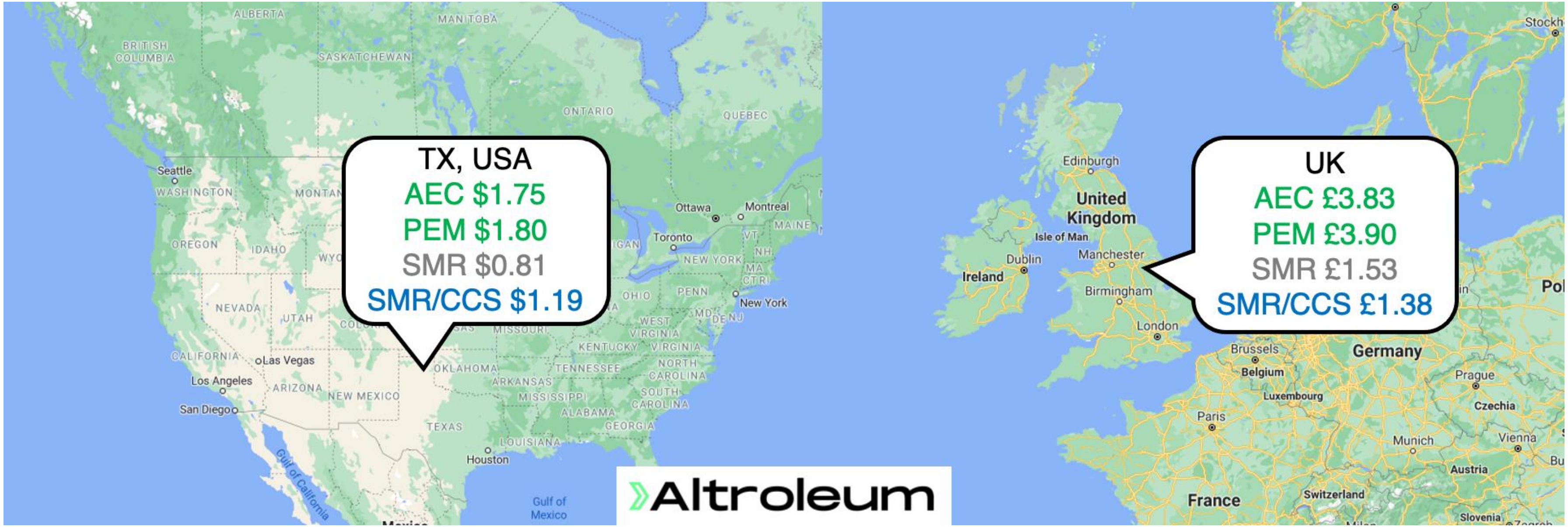

- Assessed on 9th April 2021 using Altroleum (www.altroleum.com)
- Costs shown are per kg of hydrogen, including linear capex depreciated over plant lifespan of 25 years
- Grey and blue: 100 Tonnes/day production, subjected to EU ETS carbon tariffs in the UK case, calculated using month ahead natural gas futures evaluated at the closest hub, CCS costs assume likely costs for proposed future CCS schemes
- Green: 25 Tonnes/day production (~50 MW plant), AEC electrolysis, calculated using month ahead electricity futures evaluated at the closest hub

Local blue hydrogen production avoids overseas hydrogen shipping, if local CCS is possible

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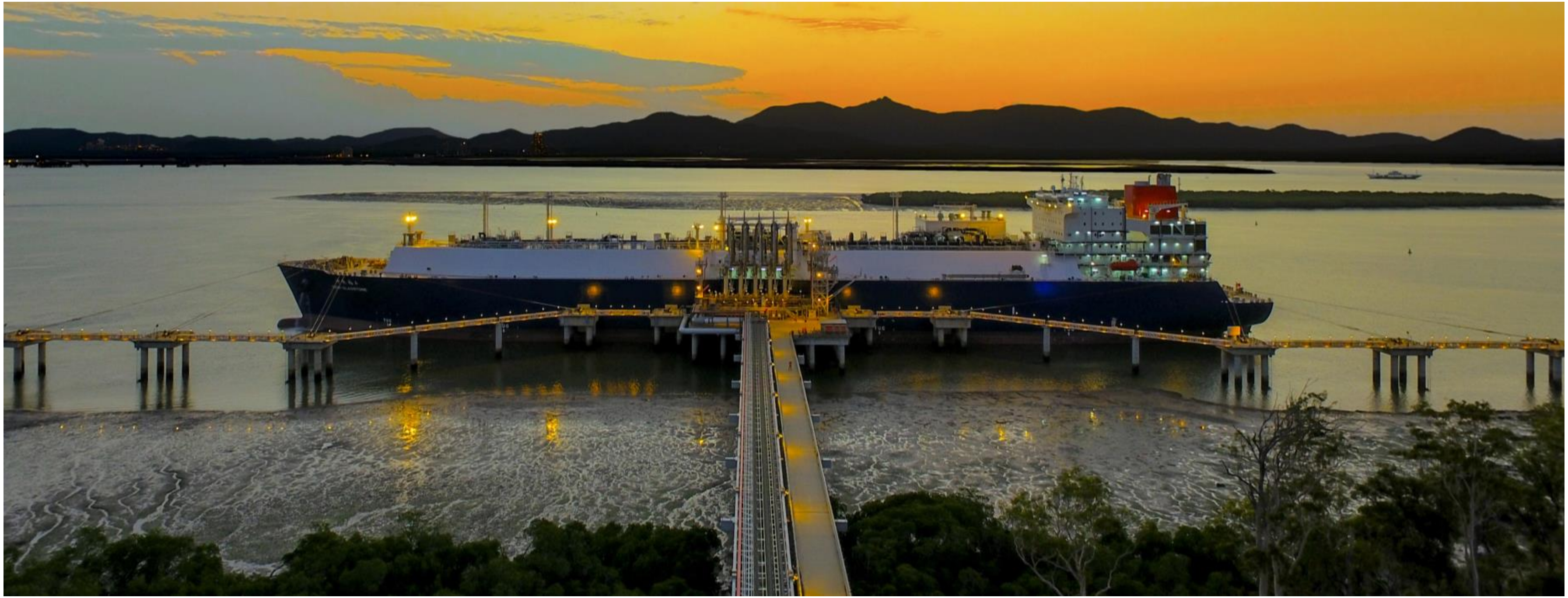

An affordable, decarbonised future will require a mix of appropriate technologies

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