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Turquoise hydrogen
Low-carbon energy for China

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2021 Carbon Peak and Carbon Neutrality Forum and the
9th Shenzhen International Low Carbon Forum
International Clean Energy Development and Cooperation Forum

Introduction to Stephen B. Harrison and sbh4 consulting

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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. He is also the international hydrogen expert and team leader for two ADB projects related to renewable hydrogen deployment in Pakistan and Palau in Asia.

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 and investment advisory experience in the energy and clean-tech sectors. Private Equity firms and investment fund managers and green-tech startups are regular clients.

As a member of the H2 View and **gas**world editorial advisory boards, Stephen advises the direction for these international publications. Working with Environmental Technology Publications, he is a member of the scientific committees for AQE 2021 and CEM 2023 - leading international conferences for Air Quality and Continuous Emissions Monitoring.

Hydrogen today – from fossil fuels.

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Coal gasification to syngas. Lu'an, China.

CCS can be expensive and energy intensive and relies on appropriate underground geology.

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CCS will be possible in some parts of China, but not all. The southeastern coastal region is likely to be most expensive.

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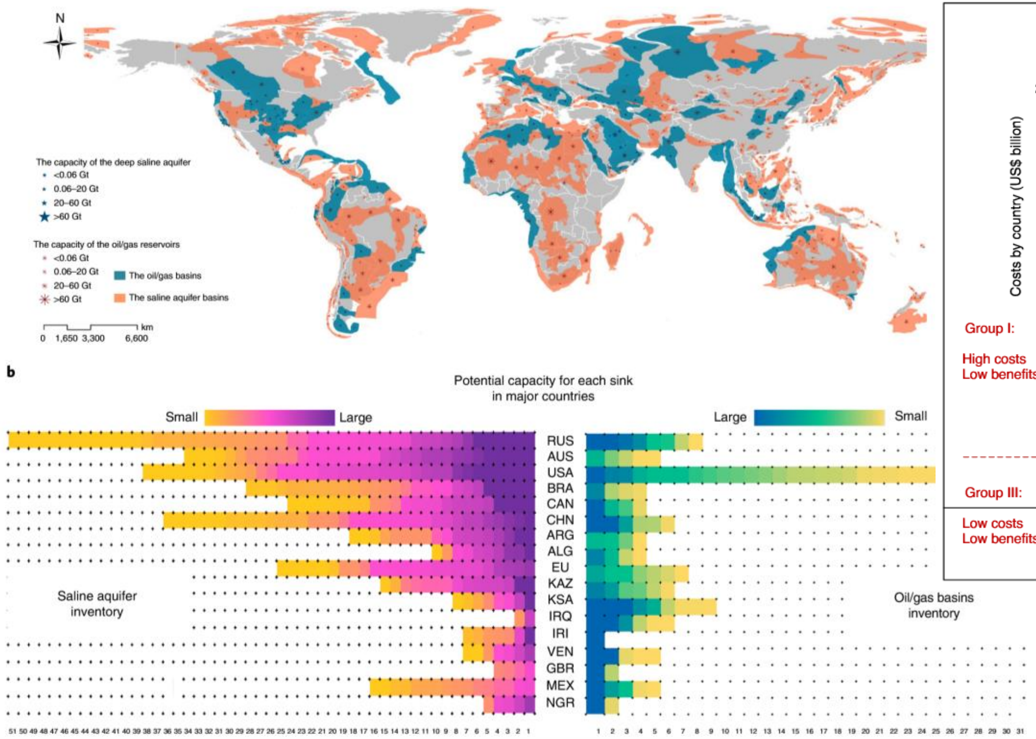

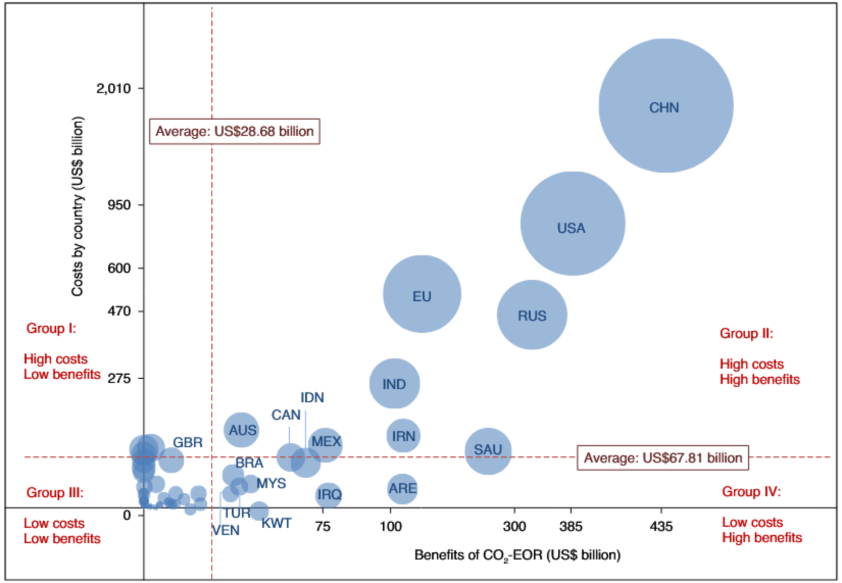

A proposed global layout of carbon capture and storage in line with a 2 °C climate target
https://www.nature.com/articles/s41558-020-00960-0?proof=t

Hydrogen – a rainbow of colours

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Brown – brown coal gasification

Purple – coal or petcoke gasification with CCS

Grey – natural gas reforming

Blue – natural gas reforming with CCS

Pink – electrolysis using nuclear power

Green – electrolysis using renewable power

Turquoise – methane pyrolysis with solid carbon

Note – colours are not internationally defined and do not specify CO2 emissions values
The colours presented here are indicative examples selected for the purposes of this presentation

Methane reforming, pyrolysis, gasification and combustion

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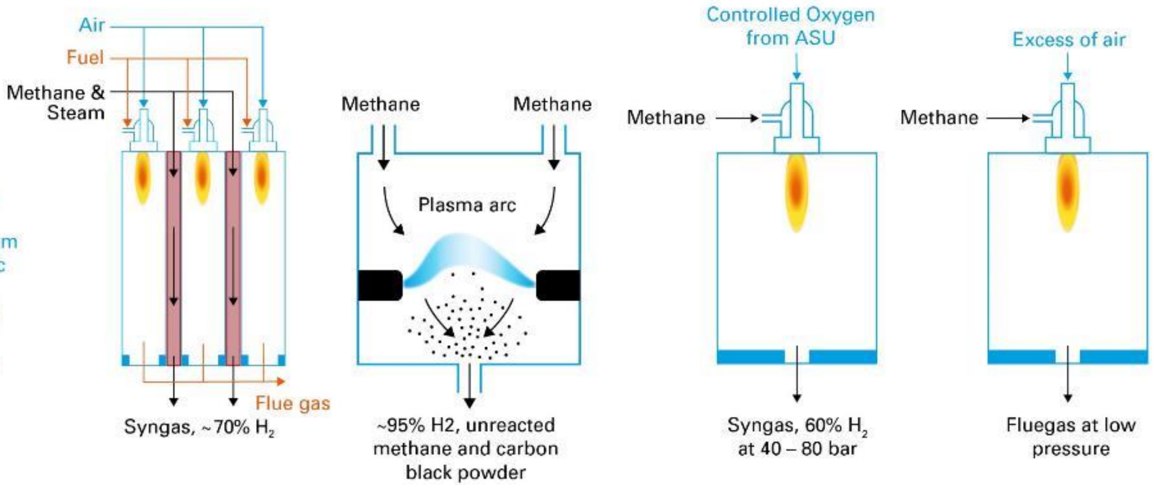
Notes:
- Energy for pyrolysis may be from combustion of fuel, or from an electric plasma arc
- Pyrolysis diagram shown is for thermal plasma pyrolysis
- POX diagram shows non-catalytic POX



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

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- Reforming combines steam and a hydrocarbon.
- Pyrolysis takes place in the absence of oxygen.
- Gasificiation takes place with a precise amount of oxygen.
- Combustion uses an excess of oxygen.

Plasma methane pyrolysis - Monolith Materials, USA

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Image copyright Monolith Materials, Nebraska

Iron oxide catalysed methane pyrolysis - Hazer Group, Australia

Image copyright Hazer Group Pty

Molten salt methane pyrolysis - C-Zero, USA

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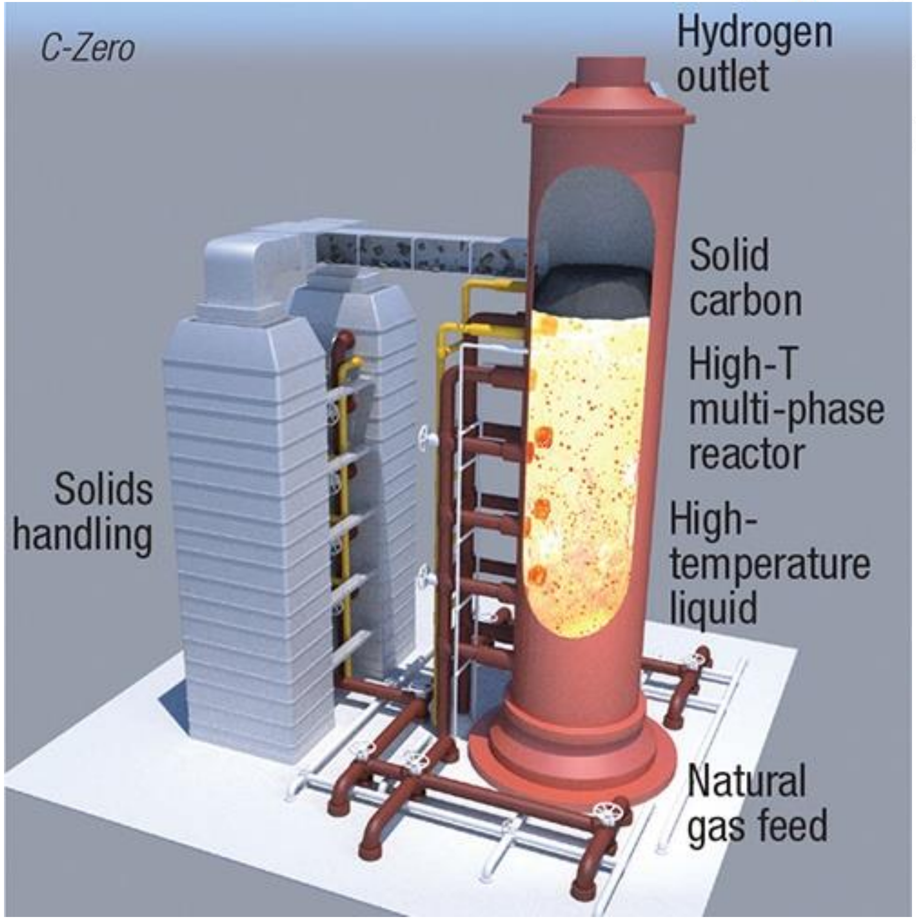

Microwave plasma methane pyrolysis for hydrogen and acetylene - Transform Materials, USA

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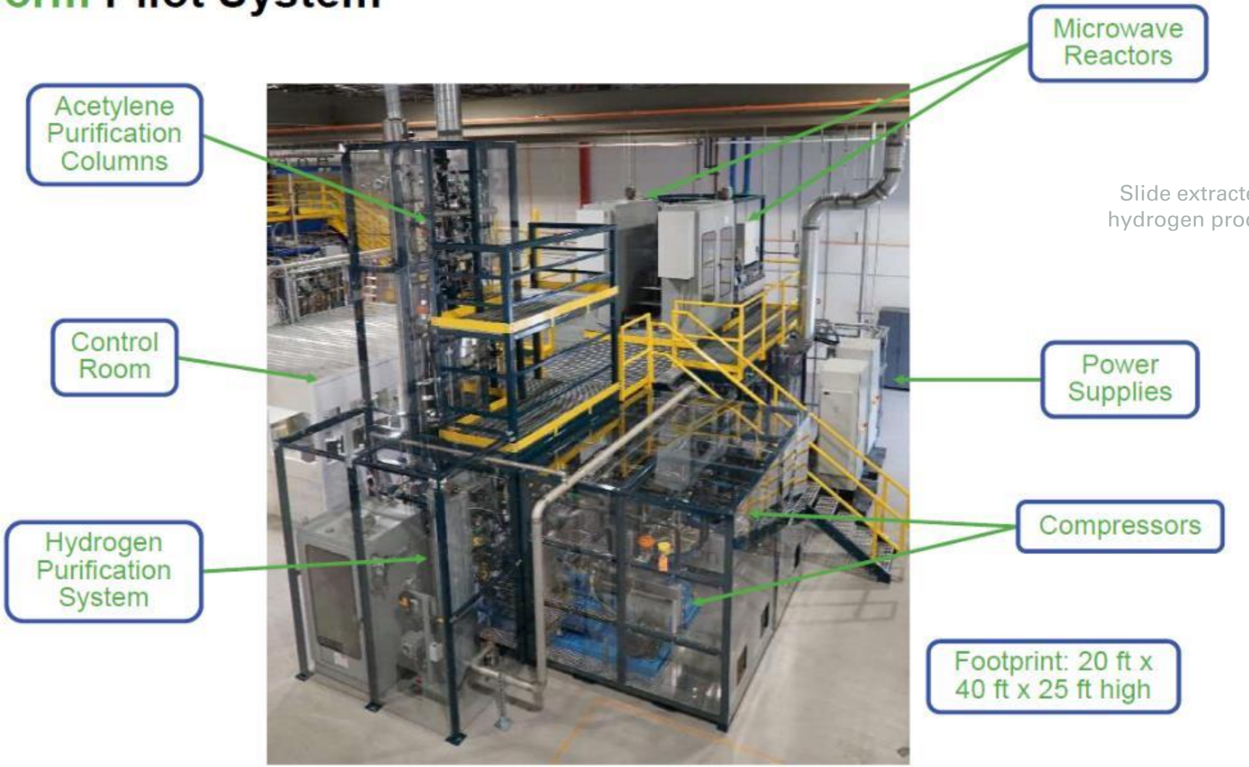
Transform Pilot System



Slide extracted from WHL “Carbon-negative hydrogen production” Webinar, 18th May 2021

TRANSFORM MATERIALS

Pulse Methane Pyrolysis – Ekona Power, Canada

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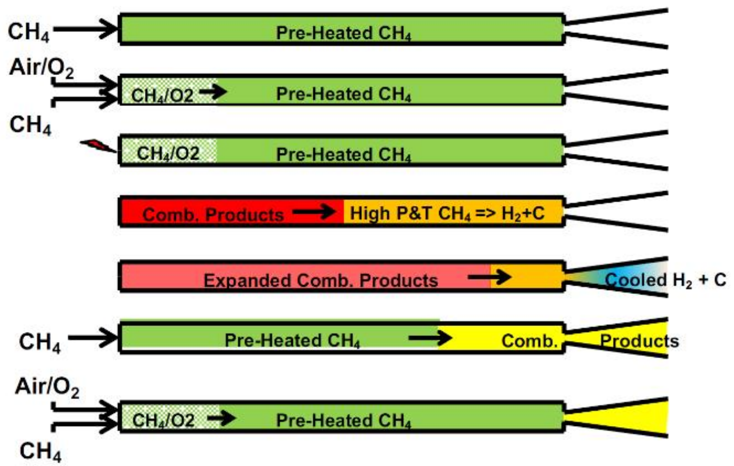
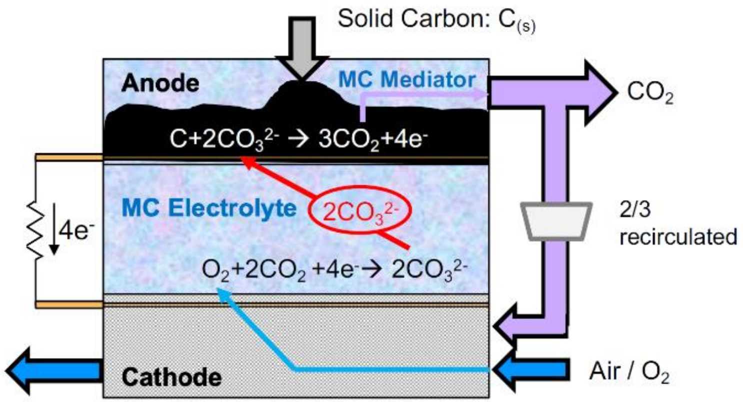
Pulse Methane Pyrolysis (PMP)



- Pulsed injection of thermal & mechanical energy
- Automatic removal of C-buildup due to unsteady flow
- Fast kinetics quenching via unsteady expansion
- Prototype reactor presently being assembled & tested
- PI Partners: Geminus Technologies, U of W, NRC

Direct Carbon Fuel Cell (DCFC)



- Fuel: solid carbon in a MC mediator
- Advantages: high efficiency + pure CO2 byproduct
- Challenges: carbon delivery to anode
- Prototype *button cell* is presently being assembled & tested
- PI Partners: NRCan-Canmet Energy, NRC

Splitting methane releases solid carbon

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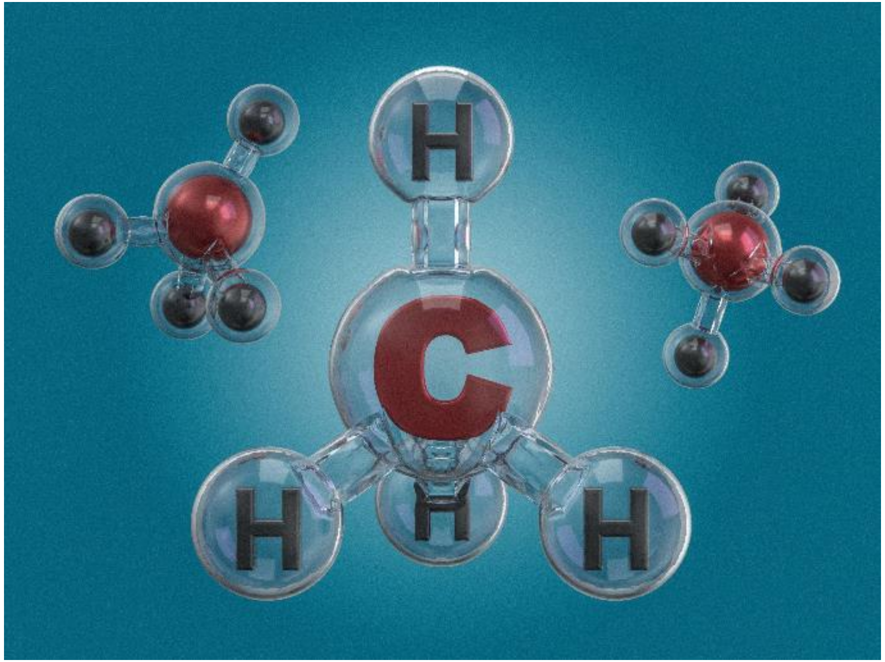

One tonne of turquoise hydrogen production releases 3 tonnes of solid carbon

$CH_4 \rightarrow 2H_2 + C$

$16 \rightarrow 4 + 12$

Solid carbon exists as many “allotropes”

Diamond

Graphite

Graphene

Soot

Coke

Carbon black

Activated carbon

Some have high value, others not

Some allotropes can easily be transformed to others

Solid carbon can be used to substitute coke for steel making or as a foundry fuel

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State of the art relies on fossil fuels

- Coke is generally produced from pyrolysis of high-quality black coal
- Significant harmful pollutant emissions result from the process
- The coke is then oxidised in the blast furnace to release CO_2 and reduce the iron or to make iron metal

Local conditions determine the most suitable low- carbon hydrogen technology

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Example location →	UK	China
Market for carbon black for tyres and rubber	Medium, European market is 2 million tonnes per annum	High, Asian market is 8 million tonnes per annum
Market for carbon as substitute for coke in iron & steel making	Low, UK annual steel production 7 million Tonnes	High, China has 55% of world steel production capacity
Natural gas source	Pipeline from North Sea	LNG terminals at coast
Underground CO_2 storage potential	High, in the North Sea	Low in coastal regions where LNG is imported
Potential to repurpose natural gas transmission infrastructure for CO_2 and CCS	High, eg Acorn project and St Fergus gas terminal can re-use natural gas infrastructure	Low, purpose built ships or new pipelines would be required to transport CO_2
Summary →	**Fits blue well**	**Fits turquoise well,**

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