# 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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Image copyright Air Products and Chemicals Inc
Coal gasification to syngas. Lu'an, China.

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

# 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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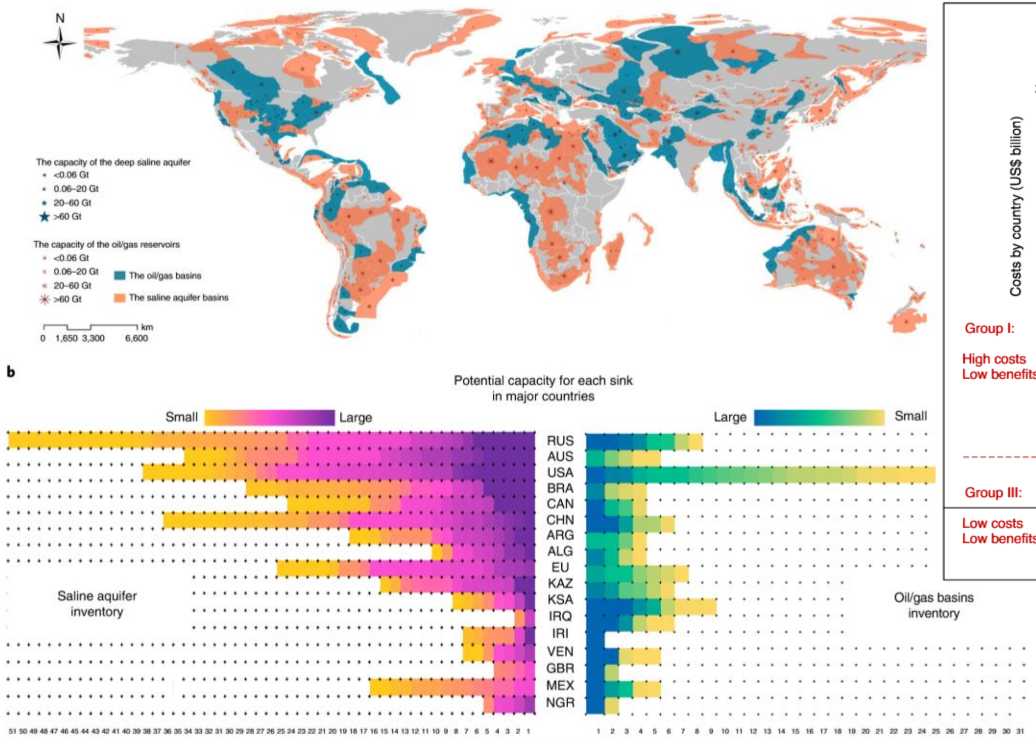


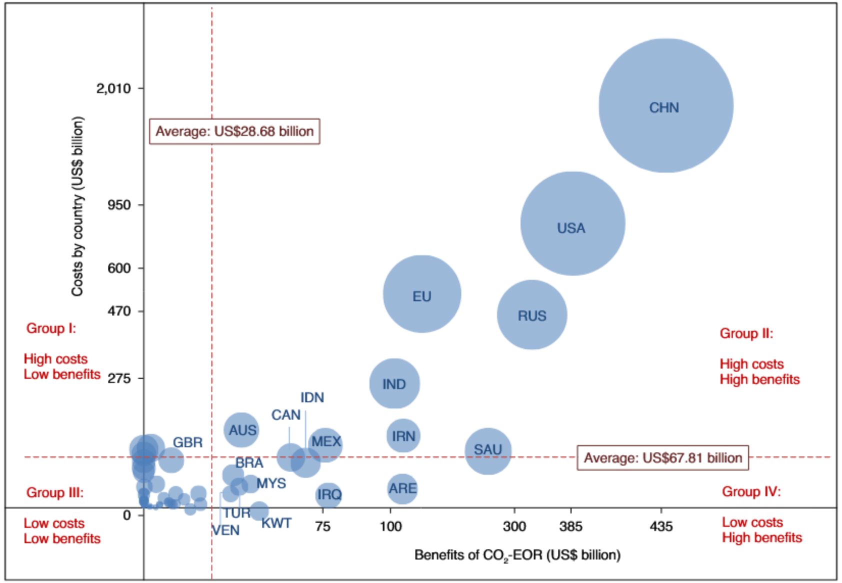




A proposed global layout of carbon capture and storage in line with a 2 °C climate target
https://www.nature.com/articles/s41558-020-00960-0?proof=t

# 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

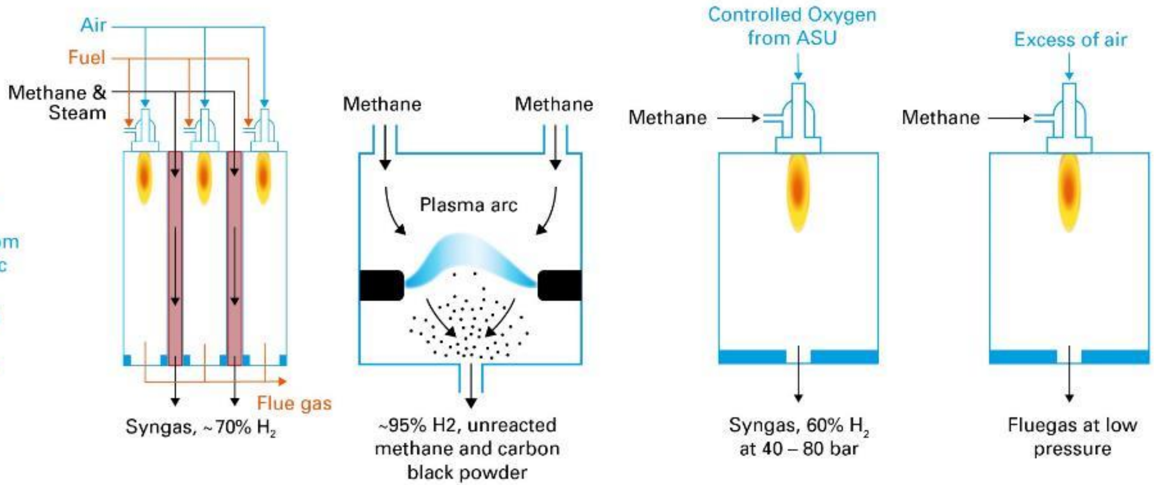


Note – colours are not internationally defined and do not specify CO2 emissions values
The colours presented here are indicative examples selected for the purposes of this presentation

## Methane reforming, pyrolysis, gasification and combustion



**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 |

- 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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# Iron oxide catalysed methane pyrolysis - Hazer Group, Australia

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Image copyright Hazer Group Pty

# Molten salt methane pyrolysis - C-Zero, USA

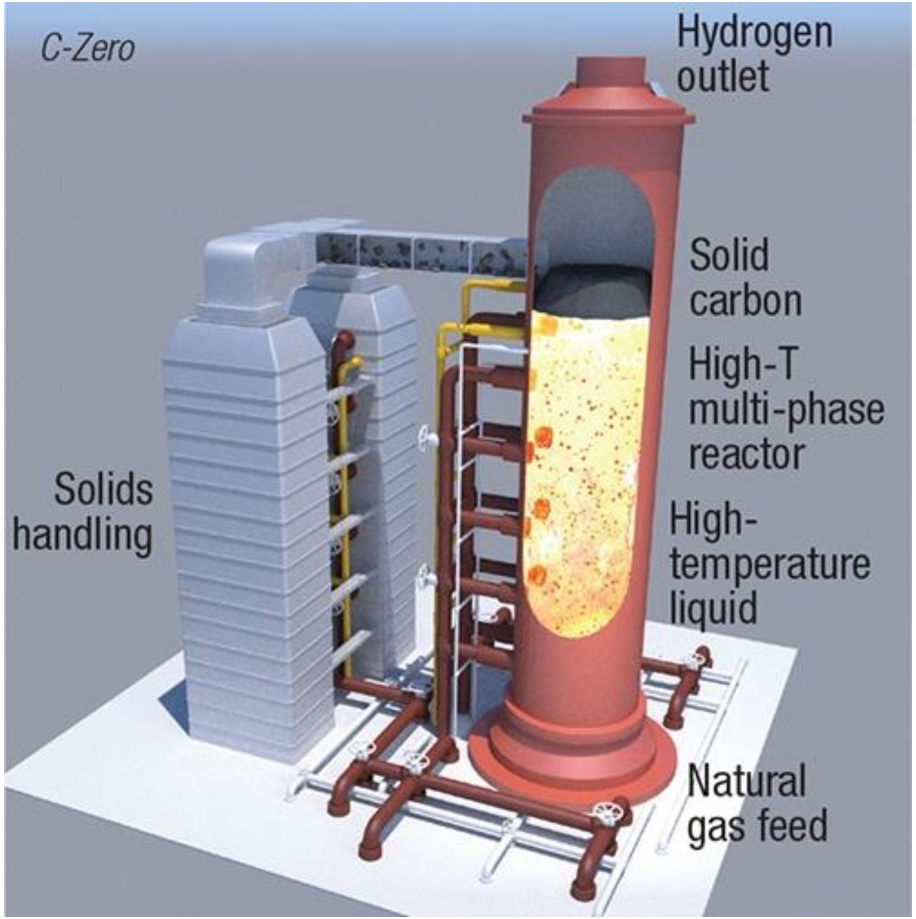


Image copyright C-Zero

# 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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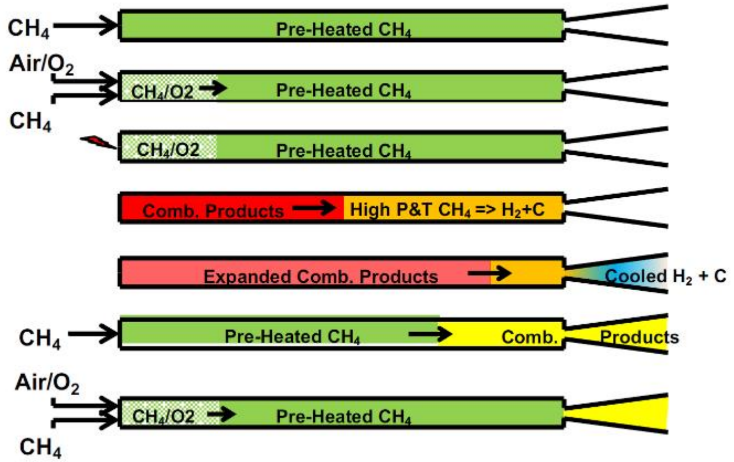
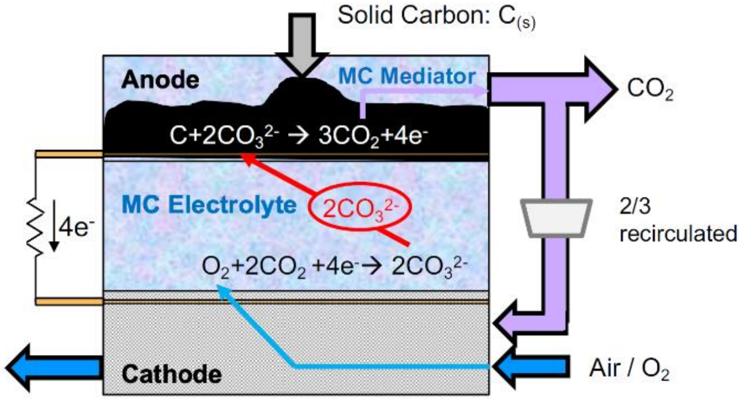
## Pulse Methane Pyrolysis (PMP)



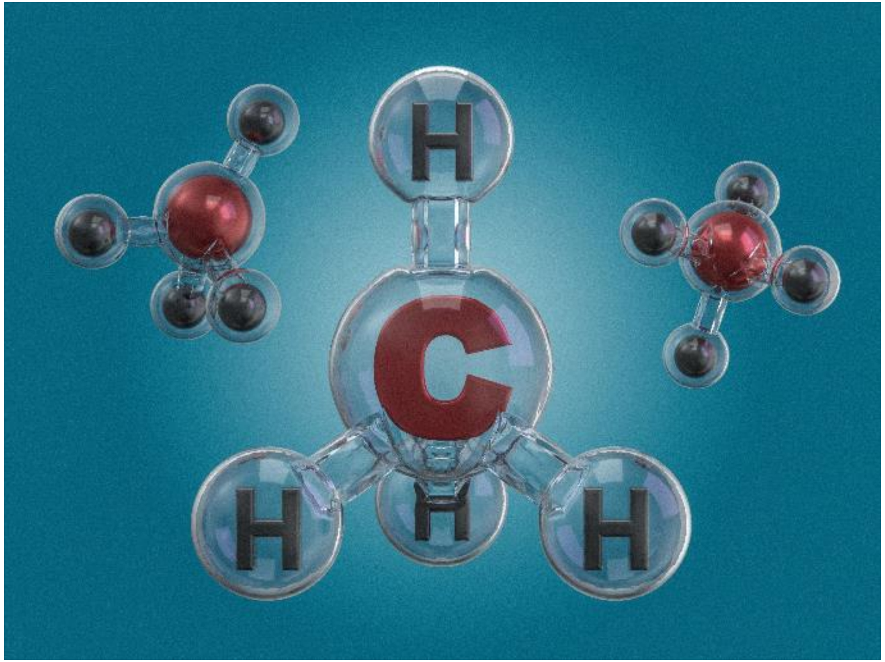

- Pulsed injection of thermal & mechanical energy
- Automatic removal of C-buildup due to unsteady flow
- Fast kinetics quenching via unsteady expansion
- Prototype reactor presently being assembled & tested
- PI Partners: Geminus Technologies, U of W, NRC

## 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




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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