Methane pyrolysis and markets for carbon

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Agenda

- The science of methane pyrolysis
- Technology and innovations
- Carbon rules the economics

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1) The science of methane pyrolysis

Methane reforming, pyrolysis, gasification and combustion

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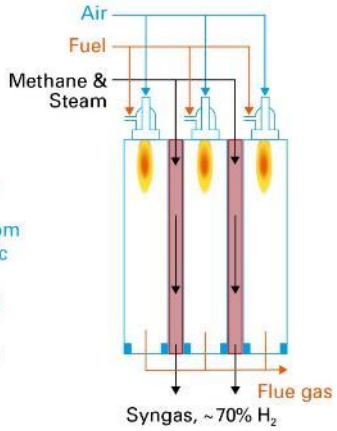
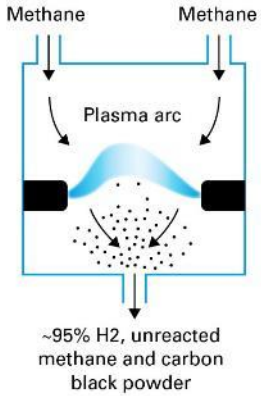
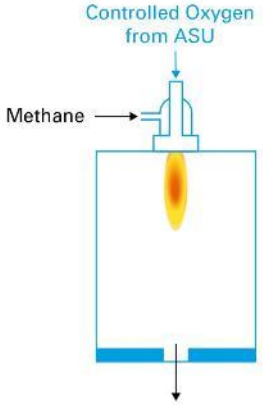
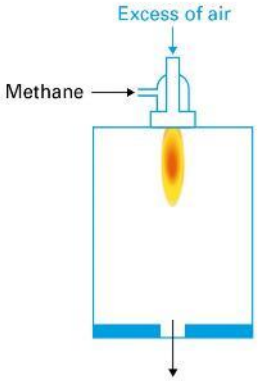
Notes:

- 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







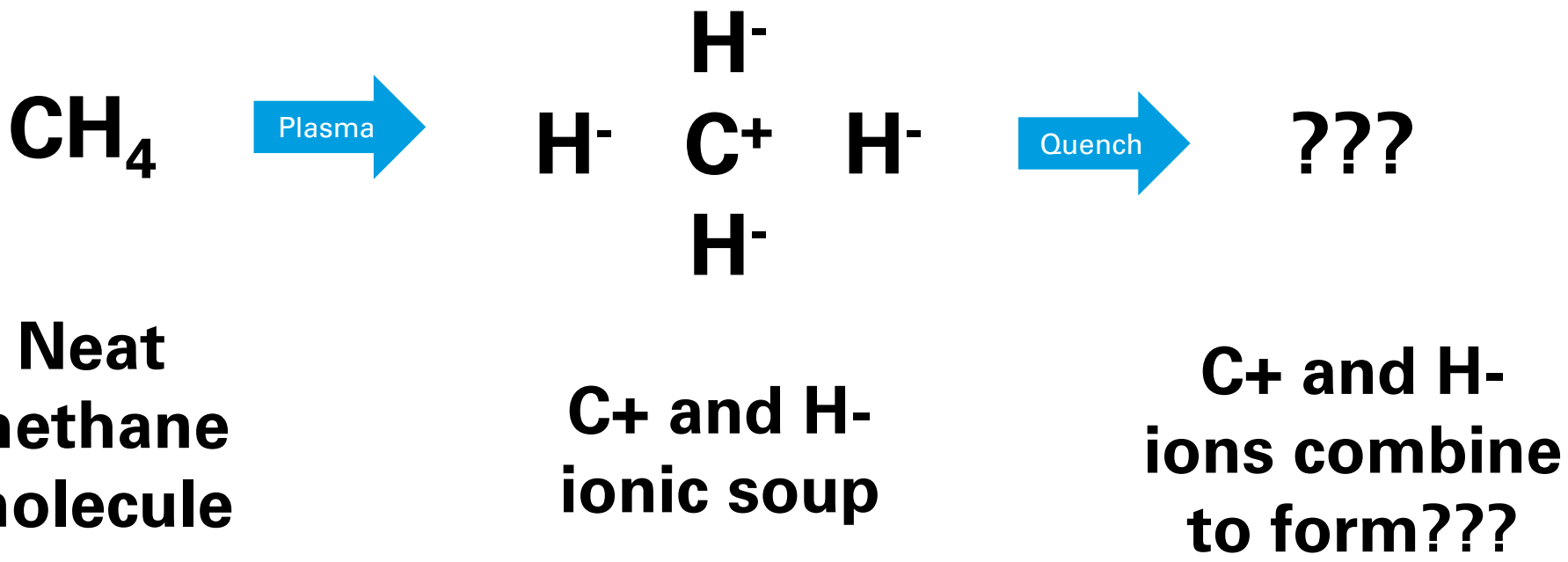


Process	Steam Methane Reforming	Methane Pyrolysis (Methane splitting or cracking)	Methane Partial Oxidation – POX (Gasification)	Methane Combustion (Thermal oxidation)
Oxygen feedstock	Oxygen is supplied as part of the water molecule with the steam	None, oxygen-free process	Oxygen from ASU	Air fed in 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

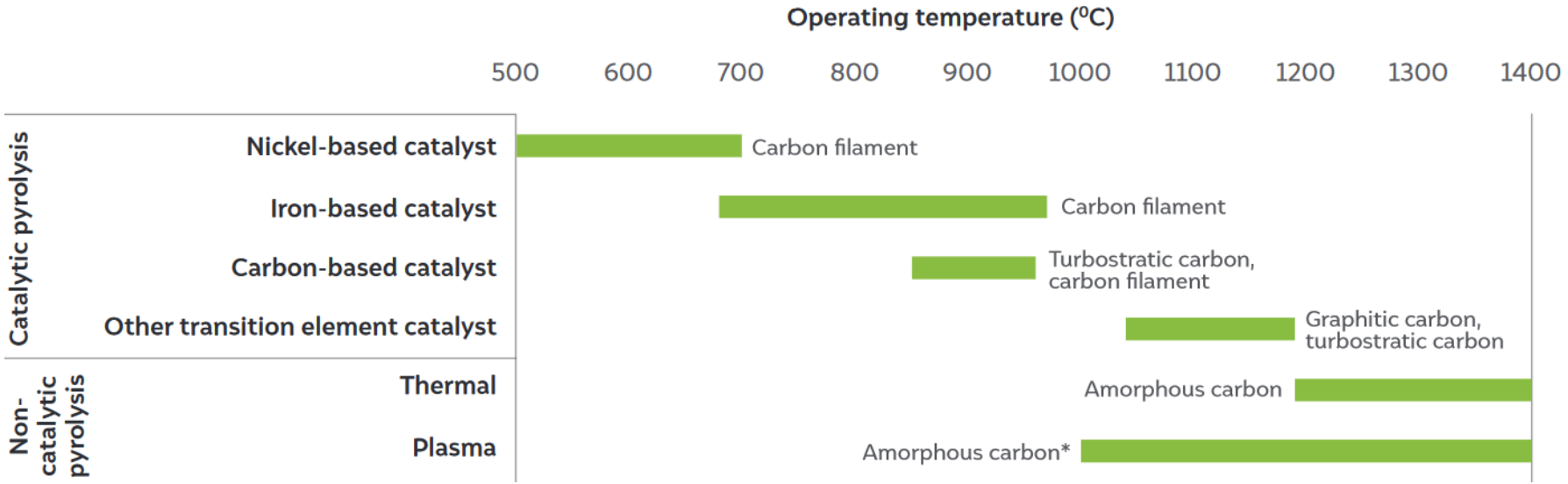
What is methane "Pyrolysis"?

- Pyrolysis takes place in the absence of oxygen.
- Reforming takes place in the presence of steam.
- Gasification takes place with a precise amount of oxygen.
- Combustion uses an excess of oxygen.

Methane pyrolysis tries to create order from chaos



Temperature, residence time and catalyst are key parameters to control the type of carbon produced during methane pyrolysis.



https://www.ceew.in/sites/default/files/ceew-research-on-natural-gas-pyrolysis-for-low-carbon-and-clean-green-hydrogen-production-india.pdf

2) Technology and Innovations

INEOS Solvents, Marl (formerly Evonik / Ashland). High temperature thermal plasma Hüls process for acetylene, solid carbon and hydrogen production.

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Hüls plasma arc reactor with downstream processing / purification. Both carbon black (up to €2,000 per tonne) and soot (sold at the value of coal) are produced.

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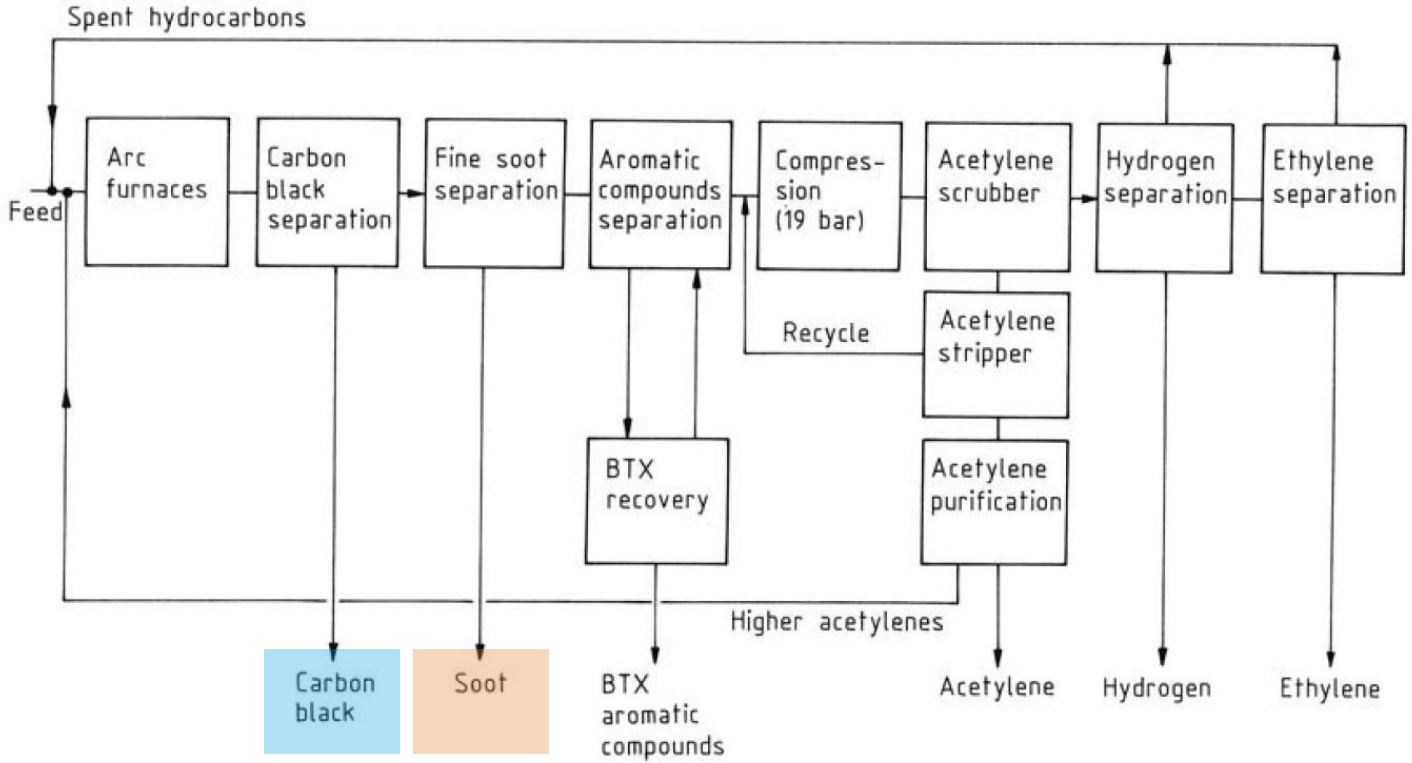

Non-thermal DC plasma methane pyrolysis - Monolith Materials, USA. Hydrogen intended for ammonia. Struggling to achieve marketable grades of carbon black consistently.

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Plenesys AC Plasma Methane Pyrolysis. Uniquely: making their own plasma torches, continuous electrode feed for un-interrupted operation and operating with AC, not DC plasma. Targeting carbon black. Commercial deployment at Turquoise Group (Pure Hydrogen Corporation) at Brisbane, in Australia.

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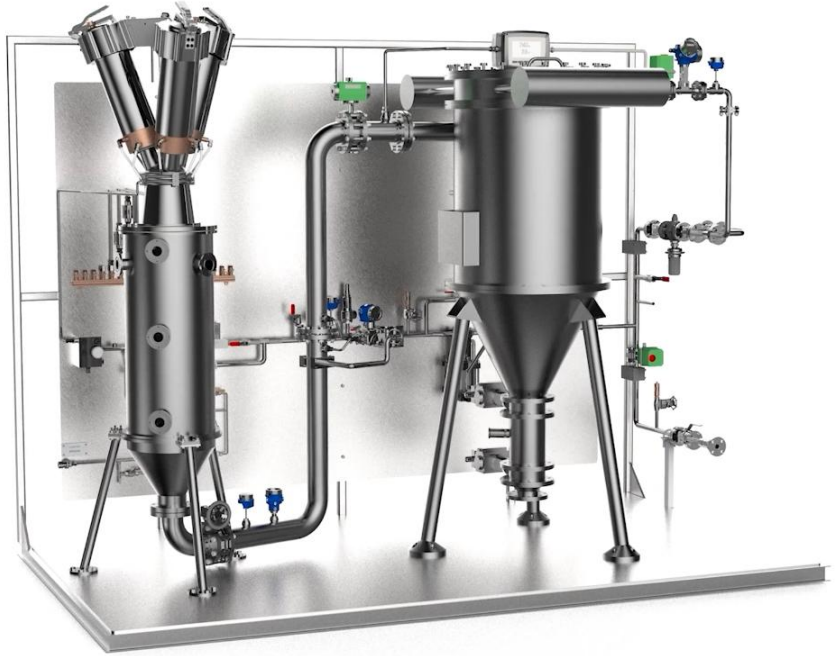

https://purehydrogen.com.au/projects/hydrogen-infrastructure/turquoise-hydrogen/

Levidian LOOP – microwave plasma methane pyrolysis, UK. Graphene production was the original goal and remains a key aspect of the business case for deployment.

- Microwave plasma to crack methane
- Solid carbon released as graphene
- Flare gas conversion target market
- Biogas / biomethane pilot in UK

3) Carbon rules the economics

By mass, splitting methane releases mostly solid carbon

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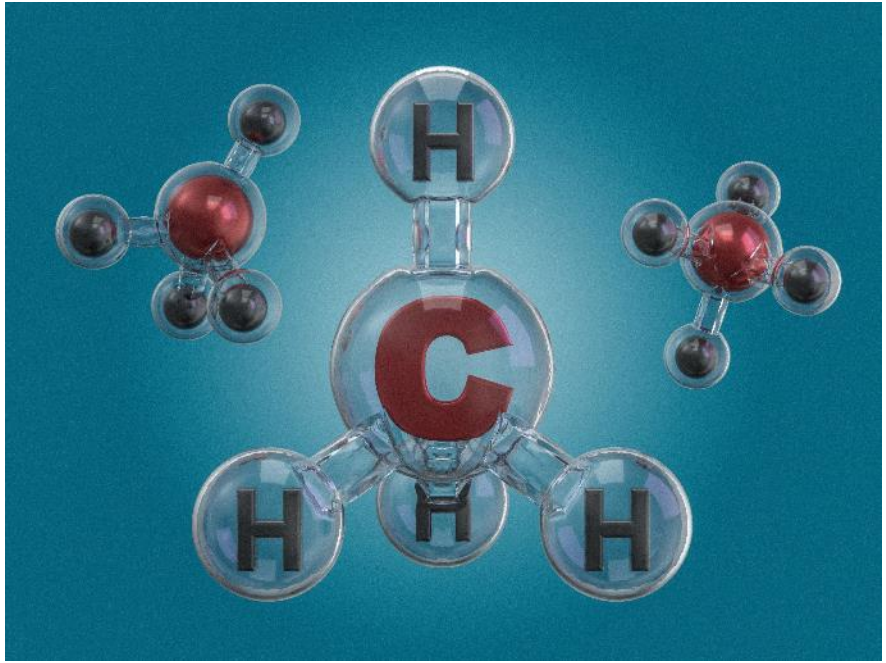

4 tonnes of methane produces 1 tonne of turquoise hydrogen and 3 tonnes of solid carbon

$CH_4 \rightarrow 2H_2 + C$

16 → 4 + 12

Solid carbon exists in many forms. Some have high value, others not. Some forms can be transformed to others using additional energy.

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1. Diamond
2. Graphene
3. Carbon nano tubes
4. Activated carbon
5. Carbon black
6. Acetylene
7. Graphite
8. Coke
9. Soot

Different forms of carbon have different value and global markets of different size.

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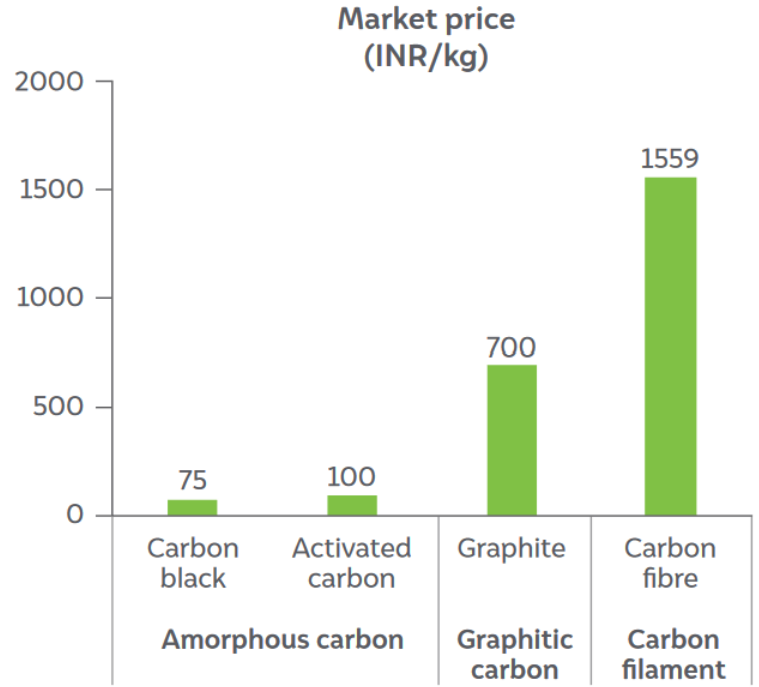

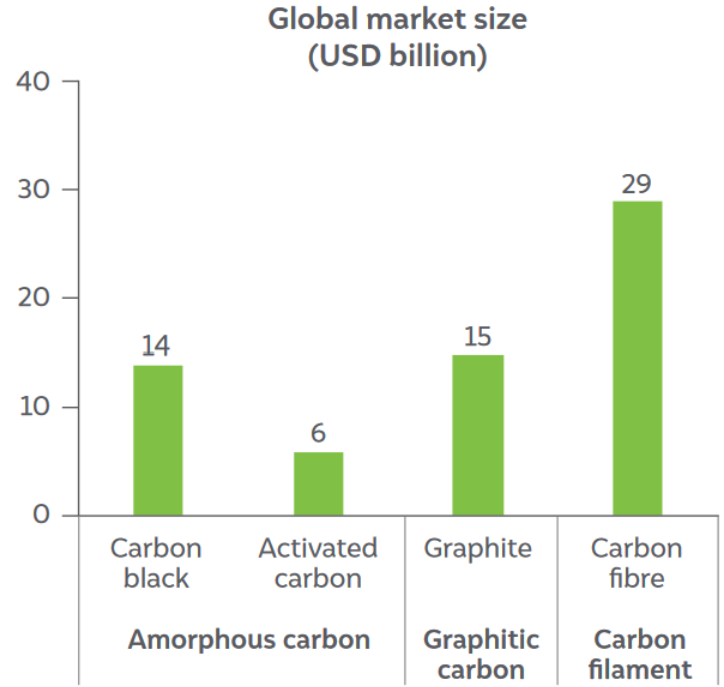

https://www.ceew.in/sites/default/files/ceew-research-on-natural-gas-pyrolysis-for-low-carbon-and-clean-green-hydrogen-production-india.pdf

Permanent storage of solid ***bio-carbon*** from ***biomethane*** pyrolysis, eg used as a cement additive may be eligible for CO2 removal (CDR) credits in future EU legislation (Carbon Removal Certification Framework, CRCF). CDR credits are currently worth around €300 per tonne of CO2 removed with buyers such as Amazon, BCG and Microsoft. This may be an attractive market for some grades of solid ***bio-carbon*** from ***biomethane*** pyrolysis.

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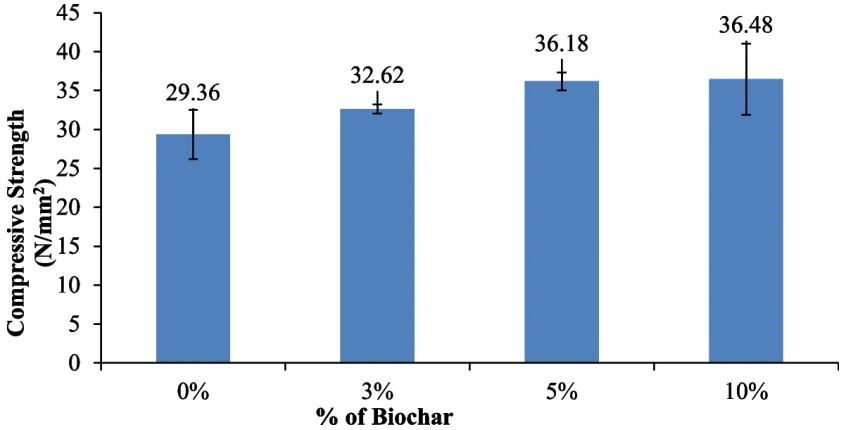

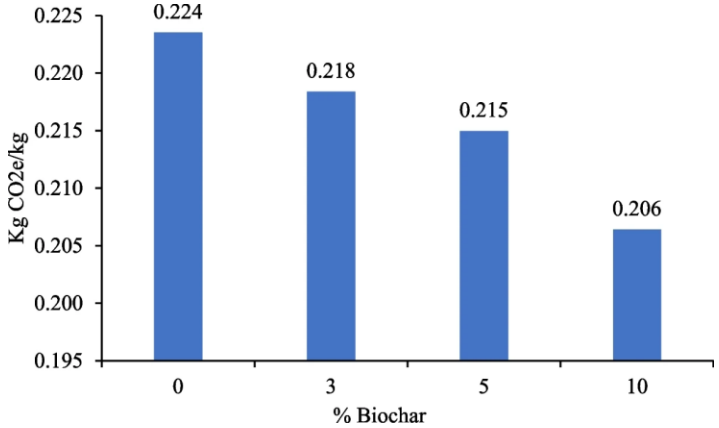

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Introduction to Stephen B. Harrison and sbh4 consulting

Stephen B. Harrison is the founder and managing director at sbh4 GmbH in Germany. His work focuses on decarbonisation and GHG emissions reduction. E-fuels, hydrogen, ammonia and CCTUS are fundamental pillars of his consulting practice.

Stephen has extensive M&A and investment due diligence advisory experience in the energy and clean-tech sectors. Private Equity firms, investment fund managers and green-tech start-ups are regular clients. He also supports operating companies in their mission to decarbonise their scope 1, 2 and 3 GHG emissions.

In 2023, Stephen evaluated seven CCTUS, hydrogen and e-fuels submissions to the European Commission's Third Innovation Fund. The fund allocated €2 billion to large-scale decarbonisation projects in Europe. In 2024 he supported the European Commission with venture capital investment due diligence and assessed eight Horizon grant applications. Again in 2025, Stephen is assessing seven Innovation Fund applications related to e- and bio-methanol production.

Stephen has served as the international expert and team leader for three ADB projects related to CCTUS and renewable hydrogen deployment in Pakistan, Palau and Viet Nam. He has also supported the IFC and world bank on e-fuels and green hydrogen strategy development projects in Namibia and Pakistan.

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 e-fuels, hydrogen, ammonia and carbon dioxide from commercial, technical and operational perspectives. For 14 years, he was a global business leader in these FTSE100 and DAX30 companies.

As a member of the H2 View and **gas**world editorial advisory boards, Stephen advises the direction for the leading hydrogen-focused international publications. Through H2 VIEW, World Hydrogen Leaders and Sustainable Aviation Futures, he has led Masterclasses covering many hydrogen, SAF and hydrogen derivatives themes in virtual and live sessions.

Stephen was session chair for the e-fuels and hydrogen propulsion track at the Bremen Hydrogen Technology Exhibition in September 2023 and chaired the same stream at that conference in Hamburg in 2024. He was also conference chair for the CO2 utilisation Summit in Hamburg in 2023 and the same event in Berlin in 2024.