

Chapter

Low-Carbon Hydrogen Technologies: Methane Pyrolysis for Production of Low-Carbon Hydrogen and Solid Carbons

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Abstract

Methane pyrolysis offers a viable route for producing low-carbon hydrogen, providing an eco-friendly substitute for traditional techniques such as steam methane reforming. This method thermally breaks down methane (CH_4) into hydrogen gas (H_2) and solid carbon, preventing direct CO_2 emissions during production. Commonly known as “turquoise hydrogen,” this approach generates a valuable solid carbon by-product, which can be captured or used in industrial processes, improving economic feasibility. The technology utilises current natural gas distribution systems, allowing for decentralised hydrogen generation while incorporating renewable energy sources to drive the high-temperature reaction. This chapter thoroughly examines methane pyrolysis, addressing essential chemical mechanisms, catalytic and non-catalytic routes, reactor configurations, and operational issues such as catalyst deactivation and carbon handling. It explores the importance of operating conditions, kinetic modelling, and new commercial initiatives by firms such as Monolith Materials and Hazer Group, showcasing scalability and market prospects. The advantages for the environment and the economy depend on aspects such as methane leaks, the carbon intensity of energy sources, and the final application of solid carbon products, including carbon black or graphite. Life cycle assessments show that methane pyrolysis, when using clean energy, can attain a carbon footprint much lower than the conventional methods. Methane pyrolysis connects fossil fuel infrastructure to a low-carbon future, positioning it as a key technology for the hydrogen economy, with continuous advancements in catalysts and reactor designs set to improve its scalability and influence.

Keywords: methane decomposition, turquoise hydrogen, low-emission hydrogen, solid carbon, carbon reduction

1. Introduction

The current global energy system is in the midst of transformation, largely driven by climate goals, technological advances, and changing markets. To push the needs for a decarbonized future, hydrogen has been identified as a leading energy carrier and thus plays a central role. Its versatility is key, because it can act as a clean fuel for

industries like shipping and aviation, a clean feedstock for chemical and petrochemicals, and more areas requiring decarbonisation [1–4].

However, a large percentage of hydrogen produced today is derived from fossil fuels through processes like steam methane reforming, which releases large amounts of CO₂. This is why developing low-carbon and green hydrogen technologies has become a global priority. In 2023, global hydrogen demand was estimated at approximately 97 Mt., a figure expected to increase to over 100 Mt. in 2024. This demand in the market represents a huge opportunity for cleaner alternatives [5–7].

A promising low-carbon alternative is by utilising methane pyrolysis, also called methane decomposition. Hydrogen produced in this manner is often referred to as “turquoise hydrogen” [8]. During this process, a molecule of methane (CH₄) is broken down using heat into hydrogen gas (H₂) and solid carbon, thus avoiding direct CO₂ emissions at the point of production. Unlike “blue” hydrogen (which captures CO₂) or “green” hydrogen (from renewable electricity), pyrolysis produces a solid carbon co-product. This carbon can be sequestered, sold, or even re-used in circular industrial processes, creating an additional revenue stream that can improve the project’s economics [6–8].

Interest in methane pyrolysis has grown due to a combination of maturing technology, market pressures, and policy incentives. The core chemistry—splitting methane into hydrogen and carbon—is a simple concept, though achieving high efficiency and continuous operation is complex due to the stability of the methane molecule as well as catalytic deactivation. While there are still many discussions around an agreed carbon pricing mechanism, pathways with low lifecycle emissions are becoming more attractive. A wave of companies like Monolith Materials, Ekona Power, and Hazer Group are now advancing pilot and demonstration plants, testing different reactor designs and technologies and bringing the technology closer to commercial reality [9, 10].

To understand the full process, the promise of methane pyrolysis must be viewed holistically. Its environmental benefit depends on where the methane comes from, how much leaks during extraction and transport, and the carbon footprint of the energy used to power the process. The final treatment of the solid carbon—whether it is used in long-lasting products or sequestered—also determines the net emissions [8].

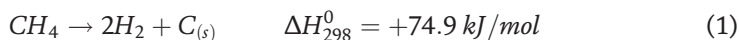
Economically, pyrolysis must compete with established methods like steam methane reforming with carbon capture. Its competitiveness hinges on natural gas prices (the feedstock of methane), energy costs, reactor design, the value of the carbon co-product, and the presence or absence of carbon taxes or subsidies. Under the right conditions, it can be cost-competitive, especially if the produced carbon is of a higher value and can be sold for a high price [6, 11–13].

This book chapter provides an integrated and holistic look at methane pyrolysis, touching on all fundamentals related to the process, including fundamental chemical reactions and catalysts to reactor designs, commercial projects currently in operation, and economic models. Starting with fundamental atomic level chemistry, and linking that with process level design and economics, this chapter hopes to provide a practical view at evaluating methane pyrolysis’ role in the energy transition [7, 8].

2. Fundamental methane decomposition mechanisms

Methane pyrolysis requires the breaking or cleaving of the strong carbon-hydrogen (C–H) bonds in the methane molecule. To achieve this requires large energy input and is normally done at high temperatures. Methane is then converted into hydrogen and solid carbon without producing CO₂ [8, 14, 15].

The standard reaction is given in Eq. (1) below:



Methane pyrolysis can typically be achieved without a catalyst at very high temperatures (usually over 1000°C), but this can be lowered through the use of a catalyst. The actual mechanism has been studied by various authors and is usually very complex, since it involves radical chain reactions and the formation of intermediate hydrocarbons before solid carbon finally deposits out [8, 14, 15].

2.1 The radical reaction pathway (non-catalytic)

For non-catalytic decomposition and thus pure gas-phase reactions, the reaction proceeds through a series of steps initiated by radical formation. The process is initiated when a methane molecule splits into a methyl radical (CH_3^*) and a hydrogen atom (H^*) [8, 14, 15].

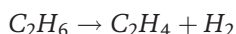
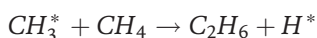
- Initiation:



This step is usually considered the slowest and requires the most energy.

The methyl radical and hydrogen atom then trigger chain reactions, with larger hydrocarbons being formed which eventually fully decompose to carbon and hydrogen:

- Propagation:



- Termination:



The chain reaction ends when radicals re-combine and thus do not take part in any further reactions.

It has been shown that the activation energy for this non-catalytic path is around 355–420 kJ.mol⁻¹. This high activation energy shows the stability of the methane molecule and necessitates the needs for a catalyst to decrease the activation barrier [8].

2.2 Catalytic pathways

By using a heterogeneous catalyst, the activation energy is dramatically reduced, resulting in lower operating temperatures. Transition metal catalysts like nickel (Ni)

or iron (Fe) have been shown to provide active sites that allow methane to decompose at much lower temperatures (600–900°C instead of >1000°C) [8, 16].

The reaction on a metal catalyst surface follows a similar series of steps without the building of longer hydrocarbon chains, however. The stepwise decomposition can be described by:

1. Adsorption: A methane molecule is bound to the catalyst surface.
2. Stepwise dehydrogenation: The methane loses its hydrogen atoms one by one, leaving a carbon atom bound to the surface.
3. Hydrogen recombination: The hydrogen atoms on the surface pair up and desorb as H₂ gas.
4. Carbon nucleation: The carbon atoms on the surface cluster together to form solid carbon.

As with the non-catalytic route, the first C—H bond break is usually the limiting step and on a nickel catalyst, the activation energy can be approximately 87 kJ.mol⁻¹, which offers a massive reduction from the pure gas-phase reaction (Figure 1) [8, 16].

Different catalysts can also play a key role when being used in the process and can also lead to different carbon products being formed. Nickel is highly active resulting in high conversions but can be quickly deactivated as carbon coats its surface due to the fast kinetics. Similarly, iron catalysts might not be as active as nickel, and they tend to form carbides that promote the growth of filamentous carbon (like carbon nanotubes). This can lead to the requirement of different

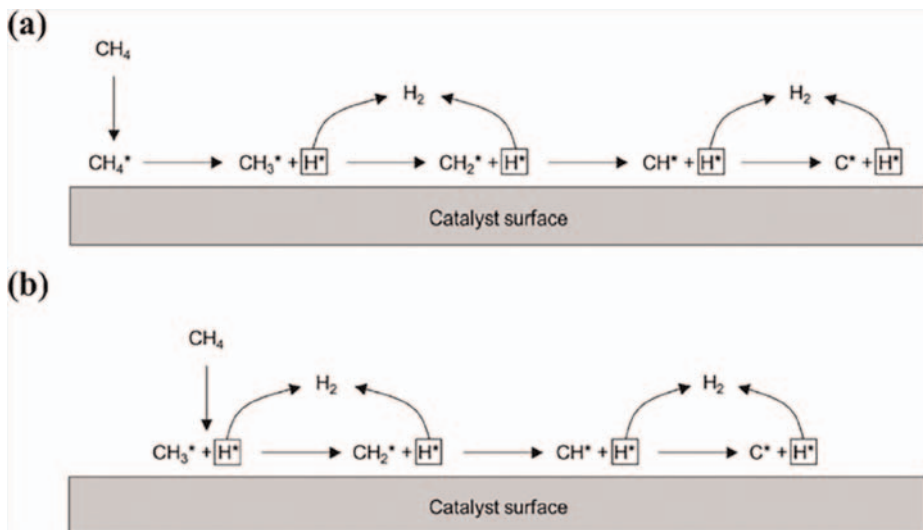


Figure 1. Mechanisms for the adsorption of methane molecules onto a catalyst surface through (a) molecular adsorption mechanism and (b) dissociative adsorption mechanism. Taken from Song and Park, 2024 [17].

catalytic packing or reactor set-ups depending on which parameter was the focus of optimization, for example nickel would favour high hydrogen yields and low-grade carbons, while iron favours high-value carbon formation with lower hydrogen yields. Some researchers have also looked at reactors in series to maximise both products [18, 19].

2.3 The role of operating conditions

The rate of the reaction and the type of carbon produced are highly sensitive to temperature, pressure and residence time since all of these affect the equilibrium of the reactions. From Eq. (1) and following the Le Chatelier principle, higher temperatures and lower pressures generally favour the forward reaction and formation of hydrogen and carbons, which then also favours deactivation on certain catalysts. High temperatures, however, also favour the formation of more ordered, graphitic carbon [8].

2.4 Kinetic modelling

To design efficient reactor models, kinetic models need to be developed to help predict how fast the reaction will proceed under various conditions. A proper kinetic model not only helps with unit (reactor) design but also plays a key role in the process design, which subsequently feeds into the economics and operational cost calculations. Common kinetic models are usually based on experimental results and include:

- Power-law models for non-catalytic systems.
- Langmuir-Hinshelwood models for catalytic systems. This model accounts for the fact that the reaction can slow down at high methane pressures as the catalyst active sites become saturated. A dual Langmuir-Hinshelwood model can also be developed when hydrogen is expected to be competing for the same active sites.
- Nucleation-growth models that specifically describe how carbon builds up on the catalyst and leads to its deactivation over time [20].

3. Reactor technologies

Turning the chemistry of methane pyrolysis into a practical, large-scale process is the duty of the reactor. The reactor's design not only controls methane conversion, but the flow and catalyst used inside the reactor also determines the type of carbon produced as well as the overall economics. The main challenge for methane pyrolysis in general is how to supply the heat efficiently while managing the solid carbon that forms, while at the same time preventing it from clogging the system and shutting the operation down [7, 8].

Researchers have explored a wide range of reactor designs, which can be grouped into a few key categories, and presented in **Table 1** below:

Technology	Pros	Cons	Other comments
Fixed-bed reactors	Simple to build and operate, excellent for fundamental studies.	Catalyst deactivates quickly as carbon coats it. Poor heat distribution creates hot spots. Requires stopping production to regenerate catalyst, making continuous operation difficult.	Often used in labs for testing catalysts. Temperature ranges from 600 to 1000°C, with methane conversion of 40–90% depending on conditions [21].
Fluidised-bed reactors	Great heat and mass transfer, scalable, suitable for continuous operation.	Catalyst particles can be worn down by attrition. Fine carbon dust can be carried away with the gas, requiring filters.	Constant motion of catalyst particles creates excellent heat distribution and allows continuous addition of fresh catalyst and removal of carbon-coated particles [22].
Molten media reactors	Natural prevention of fouling, uniform temperature, potential for very high efficiency.	Higher initial capital costs due to complex design.	Uses a bath of molten metal (e.g., tin) or molten salt. Carbon floats to the top or disperses, preventing fouling. [9, 23–25].
Plasma reactors	Fast reaction (milliseconds), compact size.	High electricity consumption.	Uses high-voltage electrical discharge or microwaves to create super-hot plasma that decomposes methane [26].
Pulsed combustion reactors	High energy efficiency, pulsation helps distribute carbon and prevent clogging.	Complexity in operation, especially pulsing.	Uses controlled, tiny combustion pulses to create intense heat waves to crack methane.
Solar-thermal (emerging concept)	Truly renewable-driven process using concentrated sunlight for heat.	Challenges in scaling and cost.	Innovative concept using giant mirrors to generate extreme heat needed for pyrolysis.
Membrane reactors (emerging concept)	Pushes chemistry to produce more hydrogen at lower temperatures.	Complexity in integrating membranes.	Integrates hydrogen-selective membranes to continuously extract hydrogen from the reaction zone.

Table 1. *Different advantages and disadvantages for different reactors used for methane pyrolysis.*

4. Catalysts and catalytic processes

For non-catalytic methane pyrolysis, high temperatures are required, and hence, a catalyst is required to reduce this high heat requirement. By lowering the activation energy barrier required to break the C-H bond, it ensures that the reaction can be operated at more manageable and practical temperatures (600–900°C). A good catalyst must be active, but also resistant to being deactivated by the very carbon it helps create [8, 16, 18, 19].

Catalysts provide a surface where methane molecules can bond and dissociate step-by-step, lowering the activation energy significantly. They also play a huge role in determining what form the solid carbon takes—whether it is disordered carbon black or valuable carbon nanotubes [8, 20]. The carbon property is determined by the elemental make-up of the catalyst, since each element can provide a different type of carbon.

4.1 Types of catalysts

Transition metals: Nickel (Ni), iron (Fe), and cobalt (Co) are the most studied because they are highly active and readily available. Each species has its own advantages and disadvantages:

Ni: Highly active but can be deactivated quickly when coated with carbon.

Fe: Tends to form carbides that promote the growth of filamentous carbon nanotubes.

Bimetallic catalysts: Combining metals can create synergistic effects. For example, adding a little copper to nickel can help stabilise it and slow down deactivation.

Carbon-based catalysts: Ironically, carbon itself can act as a catalyst. Materials like activated carbon or carbon nanotubes, especially when doped with nitrogen or other elements, can catalyse the reaction. They are low-cost and avoid the issue of metal deactivation [27].

4.2 Catalyst activity: Deactivation versus regeneration

While carbon is a desired product from the pyrolysis reaction, it is also the primary enemy for many metal catalysts due to coking, where the carbon builds up and encapsulates the active metal sites. To combat this, reactors often have regeneration cycles where the carbon is carefully burned off with air or treated with hydrogen. This, however, is not desirable where the type of carbon formed is of a high value and needs recovery. The latest research is focused on designing “carbon-tolerant” catalysts, like certain iron-based ones, where the carbon grows as filaments away from the active site, allowing the catalyst to remain active for much longer [8, 18].

5. Commercial plants and industrial applications

Over the past decade, methane pyrolysis plants have moved from lab-scale to pilot and early commercialisation scale demonstrations. The fast pace of these developments can be linked to the biggest driver namely climate policies but also market interest in low-carbon hydrogen as companies move towards global net-zero targets. Companies across the globe are now proving the technology can work at a meaningful scale [9, 10], with the main push coming from:

- Decarbonisation: Industries need a clean alternative to CO₂-heavy steam methane reforming, especially in hard-to-abate sectors.
- Economics: The solid carbon co-product—whether carbon black, graphite, or nanotubes—creates a valuable second revenue stream.

Producing hydrogen *via* pyrolysis is reported to have a carbon footprint as low as 1–3 kg of CO₂ equivalent per kg of H₂ (depending on the energy source and process methane leaks), a massive reduction compared to conventional steam methane reforming methods. Several economic analyses suggest that hydrogen can be produced competitively, especially when the carbon is sold [6, 11–13].

5.1 Key projects leading the way

- **Monolith materials (USA):** Their Olive Creek 1 plant in Nebraska uses a plasma-driven molten media reactor to decompose natural gas into hydrogen and high-purity carbon black. They sell both, with the carbon revenue significantly offsetting the cost of hydrogen production [9, 10].
- **Hazer group (Australia):** Their approach uses a low-cost iron ore catalyst in a fluidised-bed reactor. The process simultaneously produces hydrogen and high-purity graphite, a material in high demand for battery anodes. Their pilot plant has demonstrated continuous operation, a key step towards larger scales.
- **Ekona power (Canada):** Ekona uses a pulsed combustion reactor that creates intense heat waves to crack methane. This design efficiently manages the carbon, ejecting it with each pulse to prevent clogging. Their pilot unit highlights a different, innovative path to continuous operation.
- **BASF (Germany):** The chemical giant is developing a molten metal bubble-column reactor, using a tin bath. They plan to create a robust, continuous process that could be integrated into their own industrial sites for hydrogen and carbon production [25].

These diverse projects prove that there is not just one right way to do methane pyrolysis and this all depends on how the carbon by-product will be handled or formed. However, focussing on different reactor technologies and demonstrations shows both technical feasibility and a growing market interest. The future of these projects will depend on improving reactor durability, securing stable markets for the carbon, and supportive policy frameworks [7–9].

6. Integration into the hydrogen economy

For methane pyrolysis to make a real impact, it must fit seamlessly into the emerging low-carbon energy system yet at the same time compete with blue or green hydrogen technologies. Methane pyrolysis' unique advantage is that it acts as a bridge, connecting the existing fossil fuel infrastructure of today to the renewable-powered hydrogen economy of tomorrow [8]. This places turquoise hydrogen in a strategic middle ground, offering immediate low-carbon hydrogen benefits without waiting for a fully built-out renewable grid [2–4].

6.1 Leveraging existing infrastructure

A major benefit of pyrolysis is its compatibility with systems already in place today:

- **Natural gas grids:** The same pipelines that deliver natural gas for heating and power can feed distributed pyrolysis units. This allows for decentralised hydrogen production right where it is needed, avoiding the huge cost of building new hydrogen transport networks.

- Industrial clusters: The high-purity hydrogen can be fed directly into existing industrial processes, such as ammonia plants or refineries, for immediate decarbonisation [13].

When using natural gas as a feedstock, and thus still fossil-based, renewable energy sources can be used to provide the energy for the high-temperature reaction including:

- Using renewable electricity for electric or plasma heating.
- Using concentrated solar thermal energy to provide the heat directly.
- Using waste heat from other industrial processes, like steel or cement manufacturing.

This creates a hybrid system that reduces the overall carbon footprint and provides a practical transition pathway [15].

7. Carbon product benefits and applications

Unlike other hydrogen production methods that treat carbon as a waste gas (through the formation of CO₂) resulting in significant cleaning or (regulatory) penalty costs, pyrolysis ensures that the carbon can be sold. This transforms the economics and sustainability of the entire process [8].

7.1 The full spectrum of carbon products

The type of carbon produced can be tailored by adjusting the reactor conditions and formulation of the catalyst. The resulting carbon formed ranges from common industrial materials to advanced nanomaterials:

- Carbon black: A fine powder used as a reinforcing agent in tyres (about 70% of the market) and as a pigment. Replacing conventional carbon black production (which emits CO₂) with sustainable pyrolysis derived carbon black also ensures the environmental benefit.
- Graphite: High-purity synthetic graphite is essential for lithium-ion battery anodes. Demand is soaring with the electric vehicle revolution, making this a high-value target.
- Carbon nanotubes (CNTs): These are tiny, incredibly strong tubes of carbon with the exceptional electrical and thermal properties. They are used in advanced composites, electronics, and next-generation batteries. Even producing a small amount can dramatically improve a plant's revenue.
- Amorphous carbon/activated carbon: This porous, high-surface-area material is used for water purification, air filters, and gas absorption [20].

It can be seen that Fe-based catalyst mostly produces graphitic and filamentous carbons as discussed earlier. If we take the data from **Figure 2** and convert it to

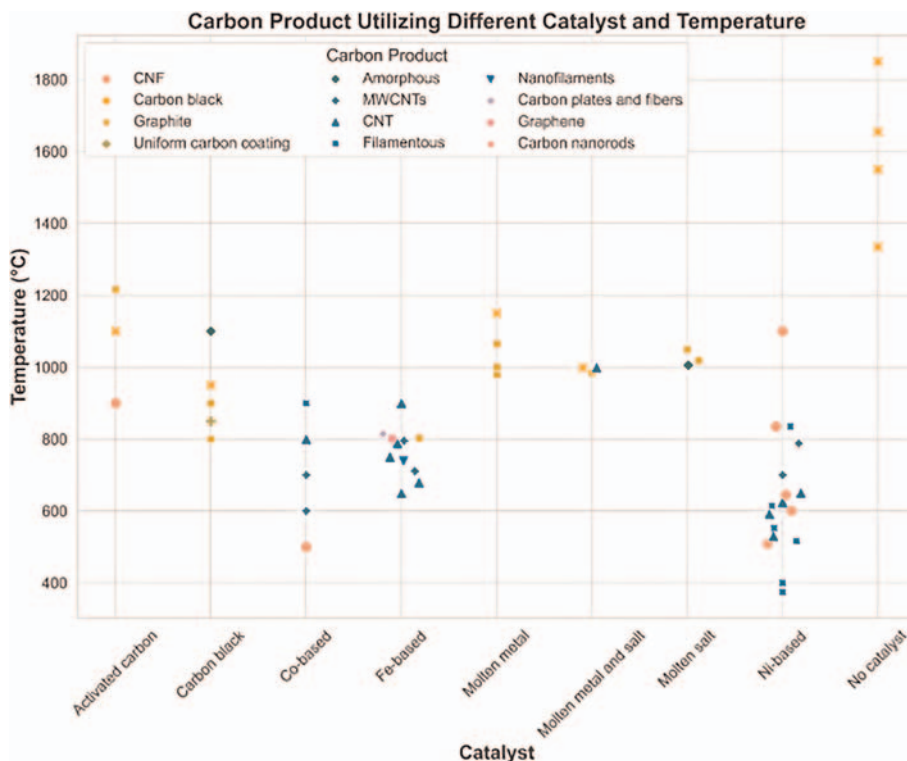


Figure 2. Different carbon species formed when using different catalyst and reactor configurations. Taken from Alhamed et al. [28].

understand how the reactor configurations play a role, the resultant figure is given below.

Data from **Figure 3** is also given in **Table 2** below for ease of reference.

7.2 Environmental and economic impact

The economic benefit of the carbon by-product cannot be ignored or overstated:

Economic lever: Selling 3 tons of carbon black for every ton of hydrogen can generate enough revenue to cover a significant portion of the hydrogen’s production cost.

Climate benefit: Every ton of solid carbon produced is a ton that is not released into the atmosphere as CO₂. If this carbon is used in long-lived products like construction materials or graphite electrodes, the process can even be considered carbon-negative, as it effectively sequesters carbon [8].

7.3 Policy and positioning

Governments are starting to recognise the benefits of low-carbon (turquoise) hydrogen. Policies in the EU and the US (like the 45 V tax credit in the Inflation Reduction Act) are creating financial incentives for low-carbon hydrogen production, which pyrolysis can qualify for if it meets specific emissions thresholds [1].

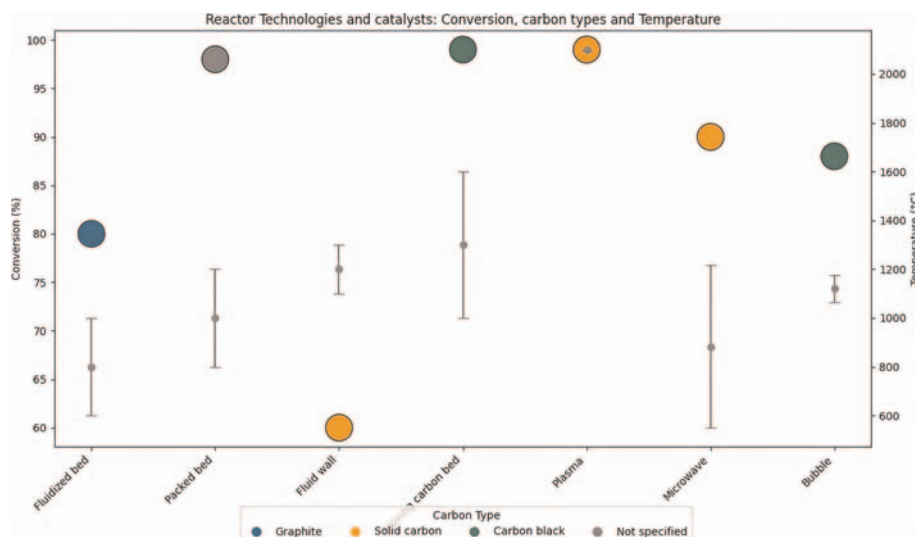


Figure 3. Different reactor configurations resulting in different carbons. Bubbles are read on the left axis (conversion); bubble colour relates to the type of carbon formed; points and error bars are read on the secondary axis (operating temperature).

Reactor	Catalyst	Conversion	Carbon	Temperature	Reference
Fluidized bed	Iron oxide	80	Graphite	900	[7, 29]
Fluidized bed	Fe/Al ₂ O ₃	80	Solid carbon	600–1000	[7, 29]
Packed bed	Carbon-encapsulated Fe nanoparticles	95.7	Not specified	800–1000	[7, 30]
Packed bed	Activated carbon	98	Not specified	1200–1400	[7, 21]
Fluid wall	Not specified	60	Solid carbon	1100–1300	[7, 31]
Moving carbon bed	Carbon granules	99	Carbon black	1000–1600	[7, 32]
Plasma	Plasma (non-catalytic)	>99	Solid carbon	2100	[7, 33]
Microwave	Coal char catalyst	90	Solid carbon	550–1216	[7, 34]
Bubble	Molten tin (Sn)	78	CNT	1175	[7]
Bubble	Molten Ni-Bi alloy	95	Carbon black	1065	[7]
Bubble	Molten Gallium (Ga)	91	Carbon black (amorphous)	1119	[7]
Bubble	Molten Ni-Sn	90	Graphite, carbon black	1000	[7]

Table 2. Overview of reactor technologies and carbon formed.

8. Techno-economic considerations

For methane pyrolysis to become a mainstream source of hydrogen, it must make economic sense. The unique twist is that its business case depends on both products formed during the cracking, that is hydrogen and solid carbon. This dual-revenue stream is its greatest advantage, but it also makes the economics more complex [6, 11–13].

8.1 What drives the cost?

The Levelised Cost of Hydrogen (LCOH) is the all-important metric. For pyrolysis, it is calculated as:

$$(Annual\ Capital\ Cost + Annual\ Operating\ Cost - Carbon\ Revenue) / Annual\ Hydrogen\ Production$$

The Carbon Revenue term is what benefits the economics as this can be seen to be reducing the LCOH from the above equation. The key cost drivers however can be broken down into the following components:

- Feedstock: The price of natural gas is the single biggest factor, making up 40–60% of operating costs. Investigations into other sources of methane (bio-methane) are investigated but sometimes have problems with scaling.
- Energy: The cost of the electricity or heat needed to drive the reaction.
- Capital (CAPEX): The upfront cost to build the plant. Reactors like molten metal systems have higher initial costs but are built for long, stable operation.
- Carbon revenue: Selling carbon black for \$1000 per ton creates a much stronger business case than selling lower-value amorphous carbon [11–13].

8.2 The power of policy (again)

Government policies are powerful levers that can tip the scales:

- Carbon pricing: A tax on CO₂ emissions makes grey hydrogen more expensive, narrowing the cost gap with turquoise hydrogen. However, because carbon taxing varies across different countries, this shows that methane pyrolysis would benefit in countries where the tax is high.
- Subsidies: Government incentives for clean hydrogen or products can dramatically reduce the effective cost of hydrogen from pyrolysis, potentially making it cheaper than fossil-based alternatives [1].

9. Environmental, life cycle assessment and circularity

A full cradle-to-grave life cycle assessment (LCA) should be used to properly measure the true environmental impact of methane pyrolysis. Such a life cycle would include the sourcing of the gas as well as the use of the final carbon product [8].

9.1 The full picture

A full LCA would examine:

- Methane leaks: If methane (a potent greenhouse gas) leaks during extraction and transport, it can significantly undermine the climate benefits. Controlling these leaks is critical.

- Energy source: Because of the high temperature requirements, the reactor heat can come from burning natural gas, which would push the emissions higher. If, however it is powered by renewable electricity or solar thermal, the carbon footprint is significantly reduced.
- Carbon's end-of-life: The ultimate climate benefit also depends on what happens to the solid carbon from the process. The benefit is limited when it is used in tyres that have a shorter lifespan, but larger improves when it is locked away in the long-lived graphite electrodes or building materials [8].

When all factors are accounted for, methane pyrolysis powered by clean energy and with controlled methane process leaks can have a lifecycle carbon footprint of just 1–3 kg of CO₂ equivalent per kg of H₂. This is a 70–95% reduction compared to conventional grey hydrogen. Furthermore, if the process uses methane from biogenic sources (like landfills or manure), the overall cycle can be considered to be carbon negative.

9.2 Broader benefits

Over and above just the climate benefits, methane pyrolysis also benefits by:

- Reduced water use: Pyrolysis uses over 95% less water than electrolysis or SMR, a major advantage in water-stressed regions.
- Circular economy: It turns a greenhouse gas into a valuable material, creating a circular carbon pathway where carbon is used and reused rather than released [8].

9.3 Biogas as a circular approach

Biogas, which is derived through anaerobic digestion of organic waste, can serve as a renewable feedstock for methane pyrolysis. Many countries limit the landfilling of organic matter due to the formation of methane, which is a more potent greenhouse gas. By rather capturing the methane from agricultural, municipal, or industrial waste, hydrogen can be produced which would limit the reliance on fossil-based fuels. The solid carbon which is also formed in the process has use cases in industries such as tyre manufacturing or as a soil enhancer. Through this process, a full circular and closed material loop is created.

Biogas does, however, present some challenges, especially related to the cleaning and upgrading to achieve high purity bio-methane, which feeds into the techno-economics of the process. A case-study for a South African facility based on biogas feed [35] has shown that hydrogen produced from biogas can in fact be competitive with green and even blue hydrogen production facilities. The same study also showed that the price of the carbon sales was one of the largest sensitivities in the economic analysis. This is also supported by many other similar studies [36, 37].

The scalability of biogas supply is however a limiting factor, which rather points to the fact that such a process favours decentralised hydrogen production facilities rather than setting up one large, centralised facility as would be the case for green hydrogen production. By valorising waste-derived biogas and its by-products, this approach aligns well with circular economy principles.

10. Future outlook and research directions

Methane pyrolysis is fast progressing and stands at a very good threshold—it has moved from a theoretical concept to a proven technology with operating pilot plants. The path going forward for the technology would focus on refinement, scaling and integration [7, 8].

The global hydrogen demand is steadily increasing with many countries agreeing to meet the net zero targets as outlined in the Paris Agreement. This hydrogen demand can best be demonstrated by **Figure 4** below which shows the projected demand for hydrogen for the top 35 countries, taken from Ref. [38].

It can be seen that a large increase in electrolytic hydrogen production is planned, with the biggest demand coming from the transport, ammonia and methanol sectors. Latest market studies, however, have adjusted the demand that can be realised with green hydrogen alone, pointing to the current high cost of green hydrogen and the premium that it demands.

Methane pyrolysis, by using existing infrastructure and reactor technologies, can fill in the short-term demand for hydrogen where industries need to decarbonize, thus, providing a bridging technology up until the point where large green hydrogen plants can provide feasible hydrogen costs.

From the discussions above, the key areas for innovations in the space of methane pyrolysis needs to focus on the following topics which would allow methane pyrolysis to be highly competitive with SMR, but at the same time addressing the low emissions required to reach net zero targets:

- Smarter reactors: The next generation of reactors should focus on modular, container-sized units for distributed production, improved materials to withstand extreme temperatures, and designs that make continuous carbon removal even more efficient.

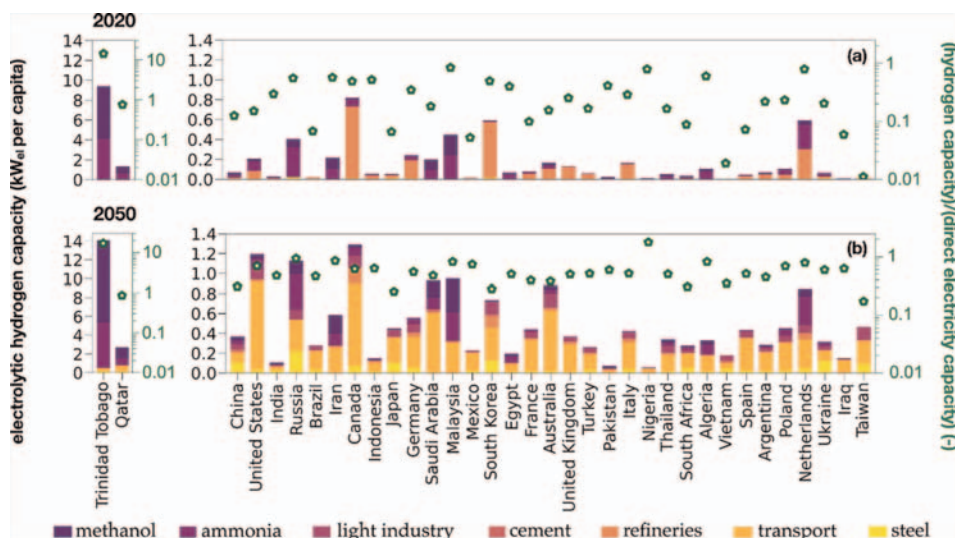


Figure 4. Global hydrogen outlook for the top 35 countries until 2050. Taken from [38].

- Next-generation catalysts: Research is pushing for catalysts that work at even lower temperatures, last longer before needing regeneration, and give precise control over the type of carbon produced. AI and machine learning are now being used to discover new, high-performance catalyst materials at an unprecedented speed.
- The circular carbon loop: The carbon loop needs to be closed, and this could involve using “renewable methane” made by combining green hydrogen with captured CO₂ (a process called methanation) and then feeding that synthetic methane into the pyrolysis reactor. This creates a cycle where carbon is constantly recycled rather than extracted from the ground [8].

11. Conclusion

In conclusion, methane pyrolysis represents a powerful and reasonable bridge to a sustainable hydrogen future. By leveraging existing infrastructure, producing no direct CO₂ emissions, and creating valuable carbon materials, it offers a compelling combination of environmental and economic benefits.


While challenges around carbon handling and catalyst longevity remain, the pace of innovation is fast and rapidly increasing with many demonstration plants at various scales coming on-line. It is thus not merely a transitional technology, but it has the potential to be a long-term player in a decarbonised world, by turning the problem of fossil carbon into a portfolio of clean energy and advanced materials [7, 8].

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