CENTER FOR CLIMATE AND ENERGY SOLUTIONS

CLOSER LOOK

Methane Pyrolysis for Hydrogen Production

September 2025

SUMMARY

Achieving net-zero emissions will require large-scale change across all sectors of the economy, and efforts to drive this transition are intensifying. Over the past several years, through the Net-Zero Pathways Initiative, the Center for Climate and Energy Solutions (C2ES) has engaged closely with leading companies across diverse sectors to examine challenges and solutions to decarbonizing the U.S. economy by 2050. As we laid out in *Getting to Zero: A U.S. Climate Agenda*, reaching net zero will require large-scale change, but it will also require us to address a number of discrete and urgent challenges.[1] To inform policymakers considering these near- and long-term questions, C2ES launched a series of "Closer Look" briefs to investigate important facets of the decarbonization challenge, focusing on key technologies, critical policy instruments, and cross-sectoral challenges. These briefs explore policy implications and outline key steps needed to reach net zero by mid-century.

Methane Pyrolysis for Hydrogen Production

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HIGHLIGHTS

Methane Pyrolysis for Clean Hydrogen

Methane pyrolysis (MP) splits methane into hydrogen and solid carbon without direct carbon dioxide emissions. Using natural gas infrastructure and modular reactors, MP can expand clean hydrogen supply while reducing transportation costs and storage needs.

Dual-Revenue from Carbon Co-Products

MP has the potential to reduce clean hydrogen prices by producing valuable carbon products alongside hydrogen. Successful commercialization of MP-derived carbon black, graphite substitutes, and other products depends on market size and product quality.

Resource and Emissions Benefits

MP uses less electricity than electrolysis and less water than both electrolysis and steam-methane reforming (SMR). Lifecycle emissions are competitive with SMR plus carbon capture, but are highly dependent on methane leakage mitigation in natural gas supply chains

Policy Support for Commercialization

Targeted public policy should seek to accelerate MP technologies to commercial success, including research funding, tax support, and incentivizing use and procurement of cleaner domestic hydrogen and carbon products. Strong methane emission standards further improve competitiveness and environmental benefits.

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Executive Summary

Current hydrogen production processes generate significant carbon dioxide emissions. Cleaner production is essential to decarbonization and building new markets but remains expensive and slow to scale. Advancing multiple clean production methods is necessary to pair each technology’s distinct advantages with their most favorable contexts, taking into consideration regional resources, infrastructure, and end uses.

Methane pyrolysis (MP) is an emerging clean hydrogen production method that splits methane into hydrogen and solid carbon, avoiding direct carbon dioxide emissions. Unlike other hydrogen production methods, MP has potential to produce valuable carbon co-products, such as carbon black, substitutes for natural, or conventional synthetic graphite, or carbon nanotubes, creating opportunity for a dual-revenue model. This could improve economic resilience and scalability for clean hydrogen.

This report examines MP’s technology landscape, attributes and advantages, engineering challenges, and commercial status. It highlights a growing field of private-sector developers advancing systems capable of flexible deployment models suitable for distributed and on-site hydrogen creation, leveraging available infrastructure.

With public policy support, MP could play a significant role in accelerating clean hydrogen deployment. Targeted federal actions include:

- **Research, development, demonstration, and deployment (RDD&D):** Federal support through grants, prizes, and partnerships can accelerate innovations for operational performance and the quality of carbon products. Cost-sharing grants and loan support for new projects and domestic manufacturing facilities can help unlock private capital.
- **Production tax credits:** Production-based tax credits for clean hydrogen and/or MP-derived carbon products are a strong enabler of early technology implementation. Credits should be predictable and durable while also ensuring that resources (e.g., lifecycle methodologies) are updated to accommodate new technologies like MP.
- **Support for domestic cleaner hydrogen and carbon products:** Demand-side support, from carbon pricing to sector-specific incentives programs, strengthen markets for clean hydrogen and MP-derived carbon products by aligning with broader energy security and economic goals.
- **Curbing methane emissions:** Policies that reduce natural gas supply chain emissions—via standards, leak detection programs, or performance programs—maximize the value of MP.

Introduction

Hydrogen is a critical commodity in major industrial and chemical processes, but today's production methods release significant amounts of greenhouse gas pollution. A renewed global effort to accelerate cleaner hydrogen production has leaned heavily into technologies like electrolysis and carbon capture with inherent limitations that will constrain their utility. Methane pyrolysis (MP), an emerging production method, warrants greater attention for its potential to overcome these limitations by leveraging marketable co-products, existing natural gas infrastructure, and modular on-site production models.

This paper examines MP across six dimensions: (1) the range of reactor technologies and business models under the umbrella of "methane pyrolysis;" (2) the advantages MP offers relative to other hydrogen production methods, as well as its emissions profile and resource requirements; (3) the potential to produce valuable carbon co-products; (4) the unique technical and commercial challenges that MP technologies must overcome to scale; (5) the current state of private-sector innovation; and (6) public policy approaches that can accelerate MP's development and deployment.

This report draws in part on interviews with representatives from eight MP companies, whose insights inform the descriptions of technologies, business models, and challenges addressed throughout the paper.

The Hydrogen Market

For decades, the global market for hydrogen has served industrial sectors such as petroleum refining, chemical manufacturing, and steelmaking, reaching approximately 100 million tons of annual production in 2024.[2] Nearly all hydrogen produced today involves the unabated release of greenhouse gases into the atmosphere. The dominant method of hydrogen production in the United States, steam-methane reforming (SMR), releases the equivalent of around 10–12 tons of carbon dioxide for every ton of hydrogen produced. As a result, about 10 million metric tons of annual U.S. hydrogen production accounts for an estimated 100 million tons of carbon dioxide equivalent each year.[3]

Key Takeaways

- **Methane pyrolysis may have favorable lifecycle emissions compared to steam-methane reforming (SMR) with carbon capture, consume less electricity than water electrolysis, and consume less water than SMR and electrolysis.**
- **Over-reliance on subsidies creates political and financial risk for the development of clean hydrogen production technologies. Methane pyrolysis may be less exposed to these risks by producing two revenue-generating products in hydrogen and solid carbon.**
- **The viability of the dual-revenue model is contingent on sufficiently large markets to absorb high volumes of MP-derived carbon while also producing carbon that meets market quality standards.**
- **MP may leverage vast, existing natural gas infrastructure, enabling modular, distributed hydrogen production free of geographic constraints, dramatically reducing hydrogen transportation and other costs.**

Domestically and abroad, cleaner production technologies are being pursued for three distinct but complementary reasons. First, they enable deep emissions reductions from existing hydrogen use. Second, clean hydrogen can unlock decarbonization in sectors that do not use hydrogen today where other low-carbon solutions may not be feasible or cost-effective. Third, it is a necessary building block for producing new products like synthetic liquid fuels which derive much of their value from the use of low-carbon hydrogen. Fulfilling these use cases could add 50 million tons to global hydrogen demand by 2030.[4]

This growth is contingent on the successful commercialization of cleaner ways to produce hydrogen at scale and at competitive prices. A portfolio of solutions will be essential to leverage the distinct advantages of each technology within their most optimal contexts.

Clean Hydrogen Production Pathways

Hydrogen use in applications like chemical-making and fuel cells result in no direct greenhouse gas emissions at the point of use. However, not all hydrogen applications are emissions-free in practice. Combustion-based uses can produce nitrogen oxides (NOx), which are harmful local air pollutants formed at high temperatures.[5] Additionally, hydrogen leakage into the atmosphere can contribute to indirect climate warming by reacting with hydroxyl radicals (OH), the main atmospheric sink for methane. This reaction extends methane's atmospheric lifetime and concentration, and also contributes to the formation of stratospheric water vapor and ozone.[6] Controlling nitrogen oxide emissions and minimizing hydrogen leakage are necessary to fully realize hydrogen's environmental benefits.

Considerations relating to the use of hydrogen notwithstanding, the primary climate concern for hydrogen pertains to how it is produced. The current lack of exploitable hydrogen reserves (i.e., geologic hydrogen) requires that it be extracted from other molecules, like methane (CH_4) or water (H_2O), before it can be utilized.

In the United States, nearly all commercial production is by steam-methane reforming (SMR), which produces hydrogen and carbon dioxide from water and the methane in natural gas. SMR captures the hydrogen and discards produced carbon dioxide into the atmosphere as a waste product.

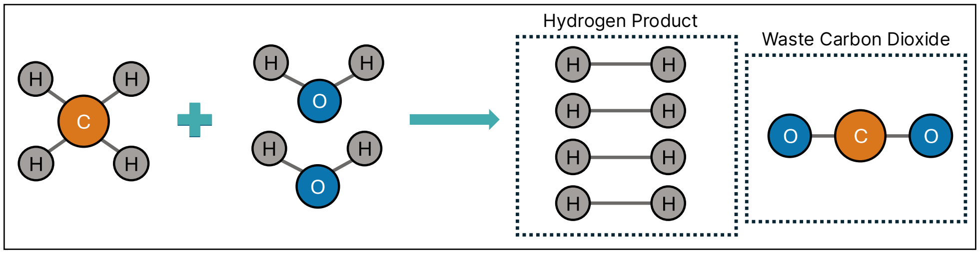
Cost-competitive cleaner hydrogen deployment will pay dividends by reducing emissions in existing markets and growing new markets and technologies that depend on low-carbon hydrogen for their value proposition. Two cleaner hydrogen production methods are currently leading the race in capital deployment and scaling: **SMR with carbon capture** and **electrolysis**. Both are relatively mature from a technological perspective and each will likely be deployed under a set of favorable conditions. However, those roles will be **limited by inherent disadvantages discussed in the "Barriers to Clean Hydrogen" section of this report**.

Steam-Methane Reforming with Carbon Capture

Methane is the primary component of natural gas. It is rich in hydrogen and characterized by four equivalent carbon-hydrogen bonds. Breaking those bonds to isolate the hydrogen requires energy.

SMR breaks methane and water steam (H_2O) into hydrogen and carbon monoxide (CO) using heat, pressure, and a catalyst. A second steam reaction (called water-gas shift) is applied to the carbon monoxide. The combined process yields hydrogen and waste carbon dioxide (**Figure 1**). An alternative but similar approach to SMR, not discussed in this report, is autothermal reforming (ATR), which integrates oxygen with steam.

FIGURE 1: FEEDSTOCKS AND YIELD, SMR AND WATER-GAS SHIFT



A simplified depiction of SMR and water-gas shift reaction inputs (methane molecule and two water molecules) and outputs (four hydrogen molecules and one carbon dioxide molecule). In the SMR reaction, methane and water steam are combined at 700–1000 degrees C at 3–25 bar pressure with a nickel catalyst. The subsequent water-gas shift subjects carbon monoxide and water steam to temperatures of 200–480 C to yield additional hydrogen.

A typical SMR plant may require about three and a half tons of natural gas to produce one ton of hydrogen when accounting for factors like natural gas composition and the energy demands of the SMR plant. Integration of carbon dioxide capture systems and ancillary equipment increases an SMR plant's energy demand and decreases plant-level emissions in an amount determined by the carbon capture rate. This does not include upstream natural gas emissions (e.g., from underground wells and equipment that extract natural gas), which are accounted for in the full lifecycle emissions (see **Table 1**).

TABLE 1: SMR PLANT REQUIREMENTS TO PRODUCE 1 TON OF HYDROGEN[7]

Inputs	No Carbon Capture	With Carbon Capture †
Natural Gas (Tons)	3.5	3.75
Electricity (MWh)	0.64	2.03
Freshwater (Gallons)	4,159	6,380
Outputs		
Hydrogen (Tons)	1	1
Carbon dioxide (Tons)	9.3	0.4
Lifecycle Greenhouse Gas Emissions		
Carbon Dioxide equivalent (Tons)*	12	4.6

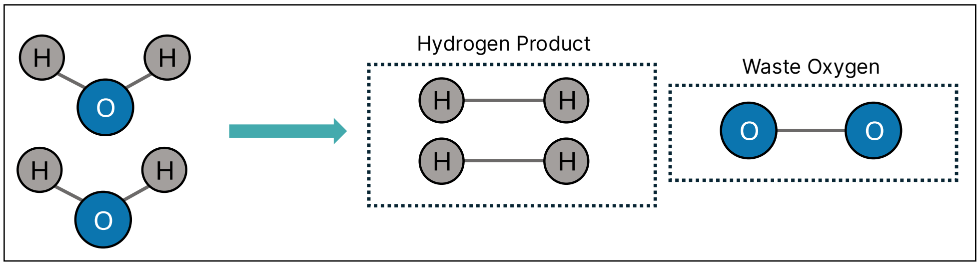
* Includes upstream natural gas emissions and U.S. average grid emissions. Upstream natural gas emissions include methane released into the atmosphere through venting, leakage, combustion, and other sources across all stages of the supply chain: production, gathering and boosting, processing, transmission/storage/pipelines, and distribution.

† Based on 96.2% carbon capture rate

Electrolysis

Electrolysis is the process of passing electricity through a device called an electrolyzer to split water molecules (H_2O) into hydrogen and oxygen (**Figure 2**). Using clean electricity results in hydrogen produced with virtually zero lifecycle greenhouse gas emissions (i.e., carbon free wind, solar, nuclear, or hydropower).

FIGURE 2: FEEDSTOCKS AND YIELD, ELECTROLYSIS



A simplified depiction of electrolysis inputs (two water molecules) and outputs (two hydrogen molecules and one oxygen molecule). Low-temperature electrolyzer technologies (e.g., alkaline and proton exchange membrane electrolyzers) operate below 100 degrees C while solid oxide cells operate at higher temperatures of 650-800 C.

Regardless of technological improvements, a fundamental minimum amount of electrical energy (237.2 kilojoules per mole of hydrogen) will always be required for water electrolysis, approximating 39.7 MWh and 2,278 gallons of water per ton of hydrogen produced.[8] In practice, these demands are significantly higher due to limited electrolyzer efficiency and the additional water needed for purification and cooling.[9] Different electrolyzer technologies rely on varying materials, catalysts, and operating conditions, which affect their overall energy and water requirements. **Table 2** summarizes these requirements for three leading technologies: alkaline electrolyzers (AEL), proton exchange membrane (PEM) electrolyzers, and solid oxide electrolyzers (SOEC).

TABLE 2: ELECTROLYZER PLANT REQUIREMENTS TO PRODUCE 1 TON OF HYDROGEN

	AEL	PEM	SOEC
Description	Liquid alkaline solution to conduct electricity.	Uses a solid membrane to conduct electricity.	Uses ceramic materials and high temperature steam
System Energy Baselines (MWh)[10]	55	55	47†
System Water (Gallons)[11]	3,800	4,800	3,800

† Includes both electrical and thermal energy inputs.

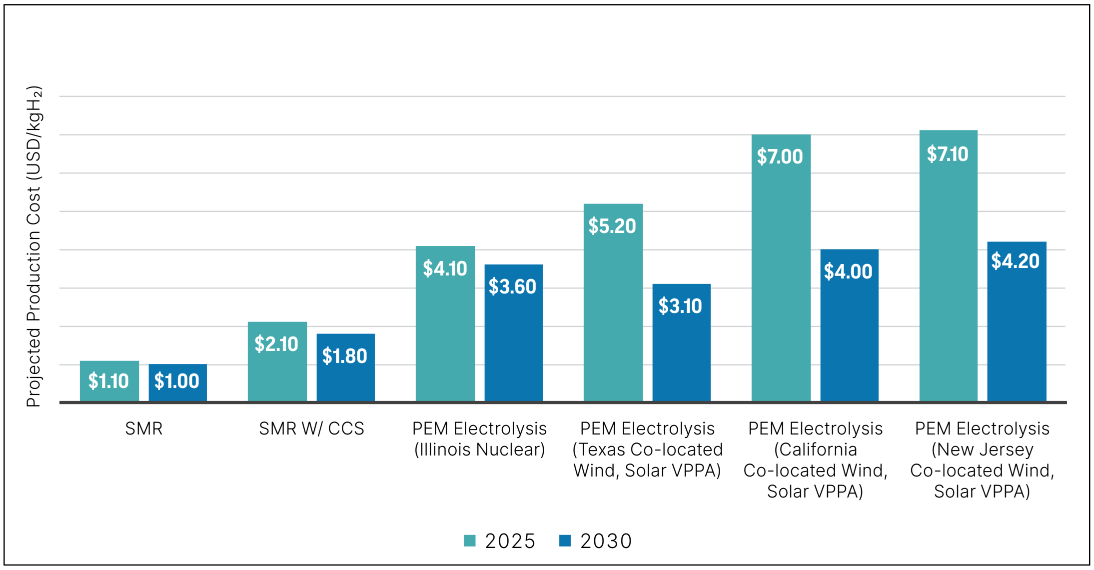
Barriers to Clean Hydrogen

The primary barrier to market success is producing and delivering (i.e., transporting) clean hydrogen at an acceptable cost. There are other market, technology, and policy challenges, but the cost of clean hydrogen is the key barrier to decarbonizing legacy users, supporting adoption from prospective users, and advancing new hydrogen-based products and technologies. This problem spans the supply chain to include both production and the costs of distribution and storage.

Production Costs

Steam-methane reforming (SMR) with carbon capture will always have higher capital and operational costs than SMR without carbon capture. Production costs using electrolysis are highly dependent on the availability of clean, cheap electricity. Therefore, electrolysis viability is location-dependent, with models of the levelized cost of hydrogen ranging significantly under various favorable U.S. locations in 2025 (**Figure 3**). Electrolyzer utilization rate is another important cost factor—with 24/7 access to clean, cheap electricity being optimal. That said, expected improvements in electrolyzer efficiency, degradation rate, and lifetimes may reduce costs by approximately 40 percent by 2030.[12] For the foreseeable future it is unlikely that electrolysis production pathways can compete with SMR on a cost of production basis alone.

FIGURE 3: MODELED LEVELIZED COST OF HYDROGEN PRODUCTION IN 2025



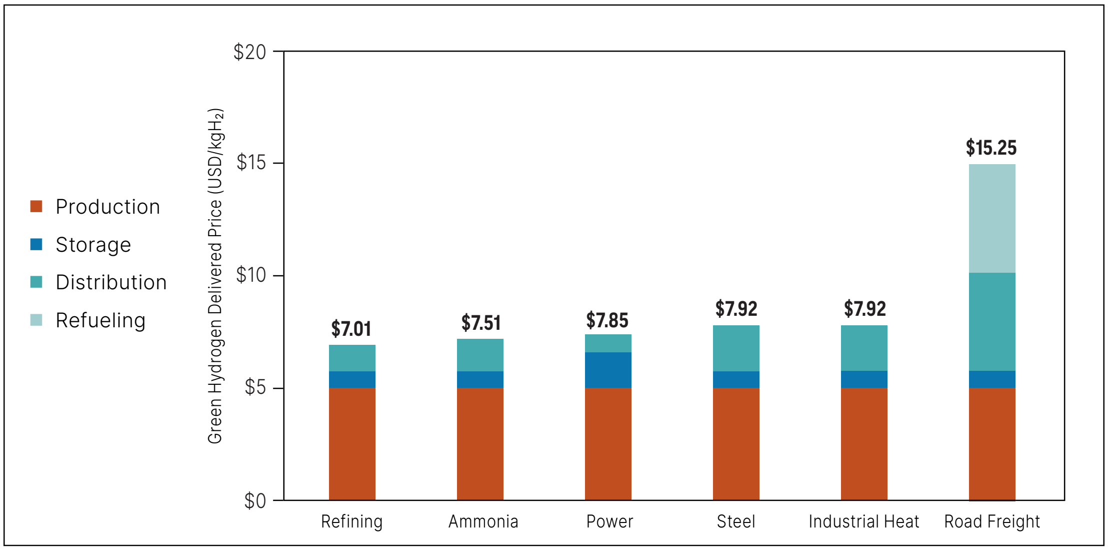
Source data: Department of Energy. Pathways to Commercial Liftoff: Clean Hydrogen. December 2024. *https://liftoff.energy.gov*.

Non-Production Costs

Hydrogen distribution and storage infrastructure is underdeveloped, and building a reliable network will require substantial investment, time, and confidence in sustained long-term demand. Transporting hydrogen is challenging. Hydrogen molecules are small and highly diffusive, allowing them to leak through pipeline materials (especially plastics) and fittings more easily than natural gas. Hydrogen absorption in metal pipelines can cause embrittlement and weaken the material over time. Its lower energy density by volume compared to natural gas requires more of it to be transported to deliver the same energy. These factors make hydrogen distribution more complex and costly than traditional gas systems.[13]

Storage and distribution costs apply regardless of the method of production. However, producing clean hydrogen in regions with favorable conditions (e.g., clean, cheap electricity) and transporting it to areas of high demand would be costly. These costs can add over $2 per kilogram to the delivered price of hydrogen, an increase of over 40 percent for hydrogen priced at $5 per kilogram. These costs can be significantly higher where clean hydrogen applications that are distributed and relatively low volume, like heavy-duty road freight stations, because they would realize higher levelized costs compared to large, centralized demand sources like refineries (**Figure 4**).[14] Together, the costs of production, storage, and distribution will limit the viability of clean hydrogen production to the conditions and locations under which each pathway performs best.

FIGURE 4: ESTIMATED DELIVERED PRICE OF ELECTROLYTIC HYDROGEN BY END-USE SECTOR

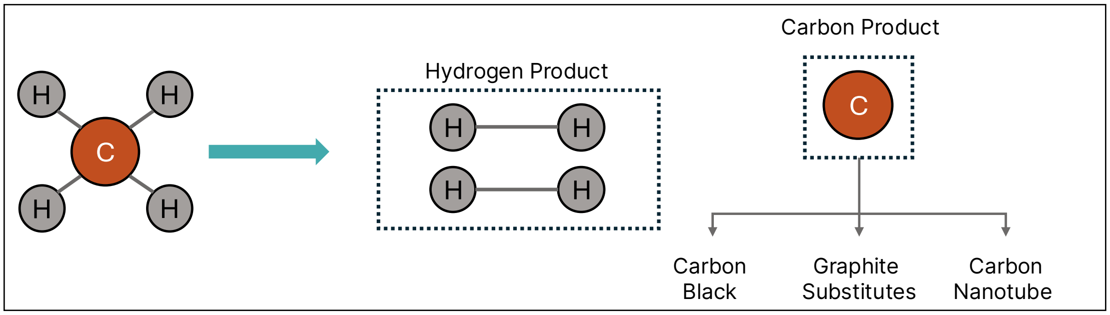


Reproduced from Roxana T. Shafiee and Daniel P. Schrag, "Carbon Abatement Costs of Green Hydrogen Across End-Use Sectors," Joule 8, no. 9 (December 18, 2024): 1–9, https://doi.org/10.1016/j.joule.2024.09.003. Estimated average delivered prices of electrolytic hydrogen by component and end-use sector. Cost data were compiled from existing literature that reported levelized costs of electrolytic hydrogen production, salt cavern and compressed gas storage, and distribution via pipeline and trucks transporting compressed hydrogen gas. Sector-specific frequency and volume of hydrogen usage can significantly add to the cost of delivered hydrogen.

What is Methane Pyrolysis

Methane pyrolysis (MP) is the process of using energy to break methane's carbon-hydrogen bonds into two products: hydrogen and solid carbon (**Figure 5**). Although "pyrolysis" traditionally refers to heat-driven reactions, methane pyrolysis is commonly used in reference to a broad range of approaches including those that are not strictly thermal, such as microwave-assisted or plasma systems. Other preferred terms may include "methane decomposition" or "methane cracking." For every kilogram of hydrogen produced, about 3 kilograms of solid carbon are also generated.

FIGURE 5: FEEDSTOCKS AND YIELD, METHANE PYROLYSIS



A simplified depiction of methane pyrolysis inputs (one methane molecule) and outputs (two hydrogen molecules and one carbon molecule). Methane pyrolysis takes place in a reactor vessel, where methane is heated to over 1000 degrees C without a catalyst or 700–900 C with a catalyst. Non-thermal methods (e.g., non-thermal plasma, microwave) may also be used.

Approaches to MP encompass a wide range of technologies, with companies pursuing diverse combinations of energy delivery, reactor designs, and catalyst usage. While these approaches are often overlapping and difficult to categorize, they share common objectives: (1) using energy efficiently to achieve desired conversion rates; (2) extracting carbon products from the reactor without interrupting the process; and (3) producing forms of carbon that have market value.

Different reactor designs and catalysts are described in the Appendix. Methods include catalytic thermal pyrolysis (the use of heat with a catalyst), *non-catalytic thermal pyrolysis* (the use of heat without a catalyst), plasma pyrolysis (the use of plasma torches or microwave plasma to split methane) and microwave pyrolysis (the use of microwaves to heat receptor or catalyst particles, which then heat the methane gas).

Each approach and design will affect the amount of hydrogen a system can produce over a given period, and the type and quality of the carbon produced, including carbon black, graphite substitutes, and carbon nanotubes. The **"Industry Snapshot"** section provides a look at some of the companies innovating through the lab, pilot, demonstration, and early commercial stages as they optimize for performance, reliability, and product quality. Catalysts are a notable challenge; they are important to reduce the temperature (and therefore the total amount of energy required) at which the carbon and hydrogen bonds are broken. However, they can interfere with and degrade the quality of carbon product produced, and can be deactivated by deposition of carbon, among other things.

Attributes & Advantages

MP is a largely pre-commercial pathway that is less mature (i.e., at a lower technology readiness level) relative to SMR and electrolysis. However, it has key advantages which directly address the shortcomings of other clean hydrogen pathways. Specifically, it has the potential to outcompete other pathways on a dollar per kilogram basis without the same resource consumption and location-based restrictions.

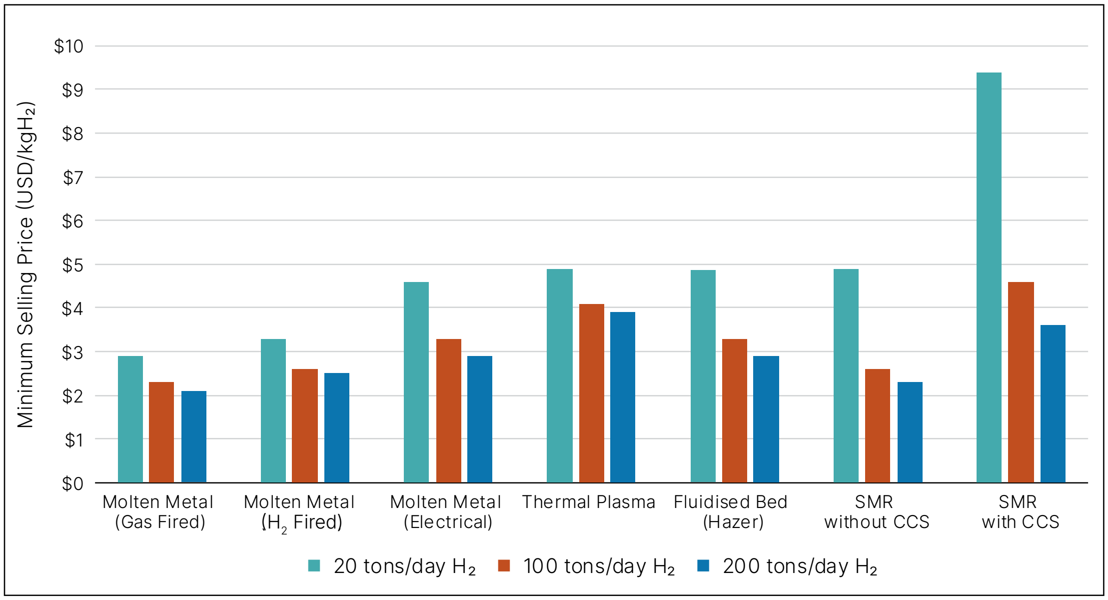
The price for clean hydrogen

The major advantage of methane pyrolysis is the opportunity to generate carbon product revenue to offset the cost of the hydrogen. The extent of this benefit depends on the marketability (i.e., quality and market size) of the specific type of carbon produced. Today, market prices vary significantly: Carbon black sells for approximately $400–2000 per ton, synthetic graphite can command prices above $10,000 per ton, and multi-walled carbon nanotubes can reach $100,000 per ton (See **Table 4**). While these prices provide market context, it is uncertain how the penetration of MP-derived carbon may affect values within these markets. See **"Carbon Products"** about market opportunities and challenges.

MP companies describe a range of prospective business models that foresee hydrogen prices competitive with conventional SMR production. Reactors which produce lower-quality carbon products, or that are optimized to maximize hydrogen purity, may rely more heavily on hydrogen revenue with pricing subsidized in part by sales of the carbon product. Other producers anticipate the carbon product to be their primary or only source of revenue, including those expecting to produce higher-value carbon products (e.g., graphitic carbon) made possible with longer reaction times (lowering overall product output). Small-scale "plug-and-play" modular reactors may allow for business arrangements offering customers hydrogen in exchange for land access, rights to the carbon product, and cost sharing agreements for natural gas and electricity inputs.

Whether MP systems and business models can compete with conventional SMR on a cost basis will depend on a wide range of factors including reactor performance, production scale, capital costs, carbon market size, and carbon product price. Techno-economic modeling performed by Marzieh Shokrollahi et al. suggests that MP systems could be cost-competitive with SMR with carbon capture and storage (CCS) at a carbon product price of $200 per ton of the carbon product (**Figure 6**).

FIGURE 6: MODELED MINIMUM SELLING PRICE OF HYDROGEN ($/KG)



Reproduced from: Marzieh Shokrollahi et al., "Methane Pyrolysis as a Potential Game Changer for Hydrogen Economy: Techno-Economic Assessment and GHG Emissions," International Journal of Hydrogen Energy 66 (2024): 337–353, *https://doi.org/10.1016/j.ijhydene.2024.04.056*. Fluidized bed data provided separately by Hazer.

The values represent model-driven estimates of hydrogen's minimum selling price for six production scenarios. Five methane pyrolysis scenarios are modeled: Three molten metal reactor scenarios (gas-, hydrogen-, and electric-powered), a thermal plasma reactor, and a fluidized bed reactor. Modeling assumes gas price $6/GJ, electricity $60/MWh, and a default price of $200 per ton of carbon black produced for the methane pyrolysis pathways. Distribution and storage costs are excluded.

Broad geographic deployment

The ability to co-locate hydrogen production where it will be used is critical to mitigating distribution and storage costs (**Figure 4**), facilitating reliable delivery of hydrogen, and minimizing the infrastructure from which hydrogen may leak and contribute to indirect climate warming.

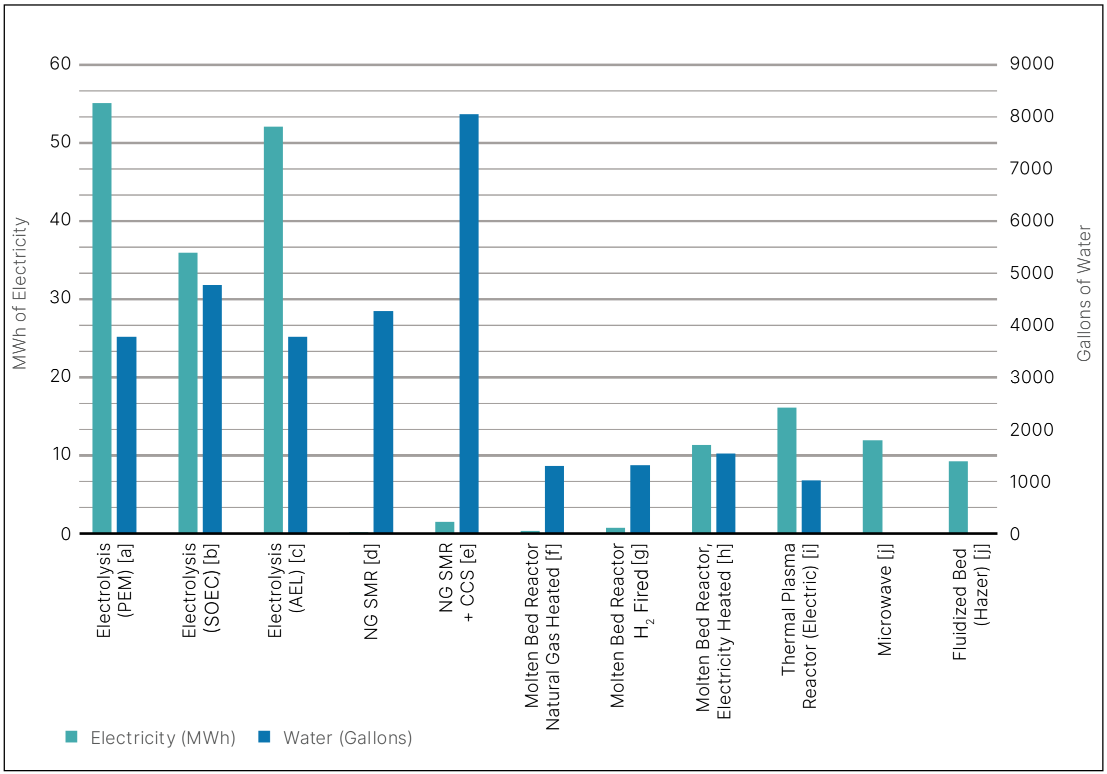
MP production can be sited anywhere a natural gas hookup of sufficient capacity is accessible. The solid carbon co-product can be transported by road or rail. This allows for on-site production in the same way that large-scale hydrogen consumers (e.g., ammonia plants) generate their own hydrogen with SMR today, and without the same freshwater requirements.

Other pathways have significant geographic constraints. SMR and electrolysis require access to large amounts of freshwater (**Figure 7**). SMR with CCS requires affordable carbon dioxide transportation or sequestration options. On-site production using electrolysis is limited to locations where an adequate supply of clean electricity is accessible (e.g., likely both behind-the-meter wind and solar). On-site electrolysis may also require more hydrogen storage capacity than MP to "overproduce" and store hydrogen that can be drawn upon during times when clean electricity isn't available.

Resource consumption

High demand for fresh water or electricity increases operational costs and may constrain the feasibility of hydrogen production in resource-limited regions. MP systems can offer advantages compared to SMR with CCS and electrolysis under these contexts.

FIGURE 7: ELECTRICITY AND WATER CONSUMPTION (PER TON OF HYDROGEN)



[a]-[e] Source data: National Renewable Energy Laboratory 2022[15]

[f]-[i] Source data: Shokrollahi et al. 2024[16]

[j] Source data: Company representations of low-end estimates

As **Figure 7** illustrates, companies developing electric-powered fluidized bed and microwave systems target to consume approximately 8 MWh and 12 MWh, respectively, to produce a ton of hydrogen. For reference, this would be about 16 or 24 percent of the demand from an alkaline electrolysis system consuming approximately 50 MWh per ton of hydrogen.

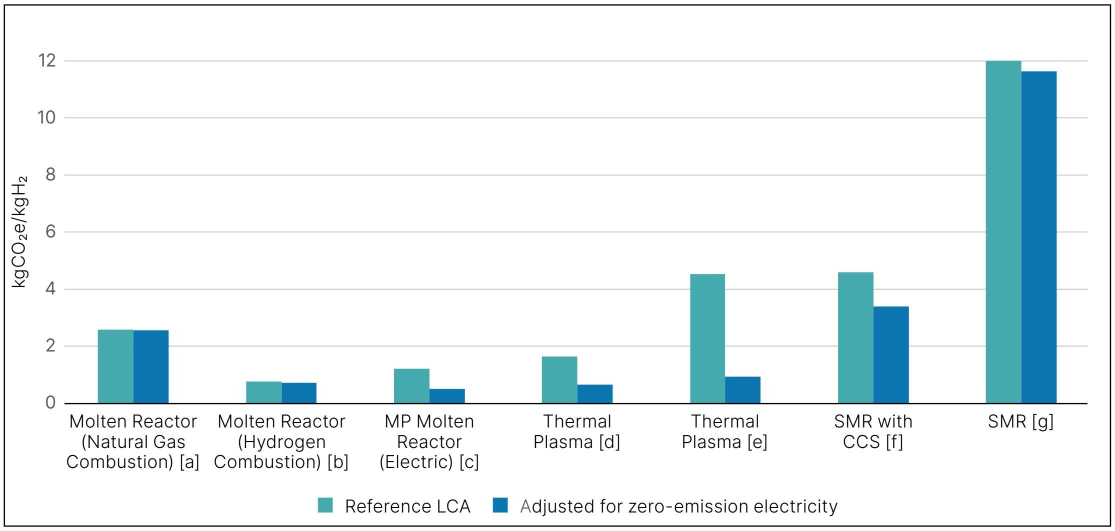
SMR and electrolysis both use significant amounts of water as a feedstock. MP systems, by contrast, may only require water for cooling purposes. MP designs with lower cooling demands, like microwave reactors, can negate the need for water altogether by integrating closed-loop cooling systems. MP's significantly lower water demand is an advantage, particularly in water-constrained locations.

Lifecycle emissions

At a minimum, most assessments of MP systems suggest comparable emissions performance to SMR with carbon capture (i.e., CCS). However, emissions are highly dependent on system design, and assessments vary based on modeling assumptions, including upstream natural gas emissions and how emissions are allocated between the hydrogen and carbon products.

Independent lifecycle assessments (LCA) are limited due to the largely pre-commercial nature of the MP technologies and lack of publicly available performance data. As a result, the LCA representations in **Figure 8** are limited to molten reactor and thermal plasma reactor MP systems from two studies ([a]-[e]). The lifecycle emissions of SMR with and without CCS are included for comparison ([f]-[g]). "Reference LCA" lifecycle emissions assume grid-mix electricity use, whereas the values "Adjusted for zero-emission electricity" deduct emissions attributed to electricity to demonstrate how the values may compare using 100 percent renewable or nuclear energy. See **Figure 8** notes for relevant modeling assumptions across the studies referenced as these may have significant implications for the values represented.

FIGURE 8: HYDROGEN LIFECYCLE EMISSIONS



[a]-[d] Source data: Shokrollahi et al. 2024. Reference LCAs use British Columbia data for electricity grid emissions (61.3 gCO_2/kWh) and natural gas supply chain emissions (1.8 gCO_2e/MJ NG). All emissions are allocated to the hydrogen product.[17]

[e] Reference LCA uses 2023 U.S. average grid emissions and allocates emissions between the hydrogen and carbon products based on mass. Steam displacement credits have been removed from the original reference LCA value.[18]

[f]-[g] Reference LCA of SMR with and without CCS.[19]

The primary LCA issue for MP systems will be the methane released upstream when natural gas feedstock is produced, treated, and transported. Notably, the natural gas supply chain emissions assumptions in **Figure 8** [a]-[d] are very low (1.8 gCO_2e/MJ is roughly a 0.36 percent leakage rate) compared to other regions and references. As **Table 3** demonstrates, the choice of upstream natural gas leakage assumptions can greatly impact LCA results, highlighting the importance of upstream leakage mitigation and the need for careful consideration when comparing different LCA studies.

TABLE 3: EXAMPLE UPSTREAM NATURAL GAS EMISSIONS FOR 1 KILOGRAM OF HYDROGEN VIA THERMAL PLASMA MP

Natural Gas Input (kg)	Leakage Rate	Methane Concentration	AR-5 GWP[a] (100-year)	Leakage Emissions ($kgCO_2e/kgH_2$)
4.624	0.36%[b]	90%	28	0.42
4.624	0.9%[c]	90%	28	1.05
4.624	2.3%[d]	90%	28	2.68

[a] Methane has 28 times the global warming potential (GWP) of carbon dioxide over a 100-year period as provided in the Intergovernmental Panel on Climate Change's Fifth Assessment Report (AR-5).

[b] British Columbia natural gas supply chain emissions used in Shokrollahi et al. 2024 (converted from 1.8 gCO_2/MJ).

[c] The Argonne National Laboratory 45VH2-GREET model uses a 0.9 percent leakage rate.[20]

[d] A study by the Environmental Defense Fund estimates 2015 U.S. supply chain leakage of 2.3% of production.[21]

Modularity

Current and prospective hydrogen users depend on high uptime and operational efficiency. This requires a reliable (i.e., uninterruptible) hydrogen supply and confidence in the performance of both production and end-use systems.

Several companies are developing compact MP reactors capable of producing approximately one ton of hydrogen per day. These units are designed for modular deployment, allowing users to scale production by adding more reactors as demand grows.

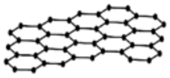
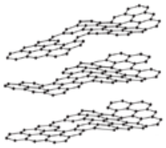
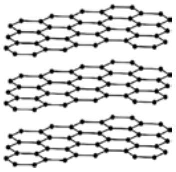
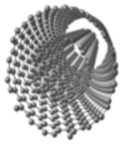
Modular systems offer greater operational flexibility by allowing maintenance or repairs without requiring full system shutdown. For customers evaluating a switch from natural gas to hydrogen (e.g., industrial process heat), questions about equipment performance are an adoption barrier. A modular approach enables a gradual transition by integrating hydrogen at low blend levels, with the flexibility to scale up hydrogen use over time.

Carbon Products

Producing valuable carbon products is the primary lever to unlocking cheaper clean hydrogen with MP. Success hinges on market acceptance of the carbon product and markets sizable enough to absorb the amount of carbon produced by MP.

There are hundreds of identified carbon structures classified by the way their atoms are bonded and arranged.[22] The properties of these arrangements determine their usefulness in practical applications. This section profiles several carbon products with known or prospective markets to demonstrate both the prospective and evidenced potential of MP as a production method, including carbon black and larger carbon particles, graphite and graphite substitutes, and carbon nanotubes. Other products may include graphene, graphitic flakes, and carbon nanofibers. **Table 4** provides context for the terminology and market considerations described in this section.

TABLE 4: AN INTRODUCTION TO CARBON STRUCTURES

Carbon structure	Carbon Black	Graphene	Amorphous Carbon	Graphite	Carbon Nanotube
					
Description	Tiny carbon particles that aggregate into a powder-like material.	Single layer of carbon atoms in a honeycomb lattice	Disordered layers of graphene	Ordered layers of stacked graphene. Naturally mined or synthetically produced.	Graphene layer(s) rolled into a tube
Value	\$400-\$2000/ ton depending on product requirments [a]	Included to contextualize references in text. See “graphite” and “carbon nanotube”.	Included to contextualize references in text. A wide range of carbon forms or products may be described as “amorphous”.	\$9,500-\$10,500/ton [b]	\$100/kg (\$100,000/ton) for multiwalled CNT [c]
Global Market (tons)	14,500,000 in 2021 [b]			Synthetic: 1,908,600 in 2020 Natural: 1,426,400 in 2020 [b]	4,382 in 2020 [b]
Corresponding Hydrogen Volume to Fulfill Global Market (tons)	4,833,000			Synthetic: 636,200 Natural: 475,466	1,461
Application categories	Tires, ink, coatings and plastics [a]			Battery, refractory, foundry, lubricant, friction product, other (e.g., steelmaking) [b]	Aerospace & defense, advanced materials, medical, batteries & capacitors, energy, chemicals & polymers [b]

Carbon structures arranged left to right by their complexity. Generally, more complex structures are both more valuable and require longer reaction times to form. Graphene Corresponding hydrogen volume to fulfill global market is based on a 3:1 carbon to hydrogen stoichiometric ratio.

[a] R. Dagle et al., R&D Opportunities for Development of Natural Gas Conversion Technologies for Co-Production of Hydrogen and Value-Added Solid Carbon Products (Richland, WA and Argonne, IL: Pacific Northwest National Laboratory and Argonne National Laboratory, November 2017), *https://www.osti.gov/servlets/purl/1411934*.

[b] Austin DeMordaunt et al., Market Analysis: Upcycling Natural Gas into Solid Carbon Products, DOE/NETL-2021/3211 (Pittsburgh, PA: National Energy Technology Laboratory, March 24, 2021), *https://doi.org/10.2172/1838316*.

[c] Kevin J. Hughes et al., “Review of Carbon Nanotube Research and Development: Materials and Emerging Applications,” ACS Applied Nano Materials 7, no. 16 (2024): 18695–18713, *https://doi.org/10.1021/acsanm.4c02721*.

Importantly, carbon products under umbrella terms like “carbon black” and “graphite” are not homogenous plug-and-play products; they can take several forms. The usability of a product requires that it meets or exceeds a certain quality standard or use-case specifications. Currently, market acceptance of carbon produced by MP is largely unproven or piloted under limited private sector partnerships. It is similarly unclear outside of largely propriety information whether MP processes can produce both significant amounts of hydrogen and more complex and valuable carbon products, like products that meet the crystalline order to be considered graphite.

Generally, there is a tradeoff between high throughput (volume/time) production of the hydrogen and carbon products and the complexity of the carbon product because more complex carbon products (e.g., carbon black being the least complex and carbon nanotubes being the most complex) generally require longer reaction times to form.

Carbon black and larger carbon particles

Carbon black (CB) is primarily used as a reinforcing agent in rubber products like tires, with lesser use in inks, paints, and plastics. High-quality forms of CB have applications as a conductive material in battery manufacturing depending on particle size and structure.[23] CB is produced today by burning tar or petrochemical oils using a process that emits large amounts of carbon dioxide (29-79 million tons per year) and pollutants that are a risk to human health like smog-forming carbon monoxide and volatile organic compounds, sulfur oxide, nitrogen oxides, and fine particulate matter.[24]

Natural gas offers the potential to serve as a cleaner and more cost-effective feedstock, enabling lower process emissions and yielding carbon materials with higher elemental purity than conventional CB production. Importantly, CB is a category of products each with their own characteristics and classifications, with quality based on purity and form, ranging from amorphous and highly disordered to more crystalline and structured (graphitic).[25] The ability to substitute legacy CB production with methane pyrolysis will depend on producers' ability to meet the purity, particle size, and structure requirements of potential customers. This remains largely unproven with the notable exception of Monolith, which in a partnership with Goodyear demonstrated use of its CB in a high-performance tire (see **"Industry Snapshot"**).

The global CB market is growing but relatively small, at about 14.5 million tons per year. MP systems producing carbon black as a coproduct would need to generate only around five million tons of hydrogen, roughly half of U.S. demand or five percent of global hydrogen demand, to fully satisfy the current carbon black market (**Table 4**). Consequently, long-term market growth of CB is important for these MP systems. Market analysts project compound annual growth rates (CAGR) of the CB market between 4.1 and 8.0 percent, with the growing automotive industry as a major factor.[26] The use of CB's reinforcing properties in tires may be particularly valuable to accommodate the higher rates of tire wear seen in electric vehicles.

Alternatively, some developers are looking beyond CB to produce larger, sand-sized carbon particles that would be less constrained by market size. These particles, which are up to 1000 times larger than CB, would be used in high-volume applications such as mineral sand for concrete, asphalt, road base, and construction fill. Construction sand alone, while extremely cheap, has a global market exceeding ten billion tons.[27] In addition to a larger volume market to offtake the carbon product, entry into those applications could potentially replace more expensive and more emissions-intensive materials.

In summary, CB derived from MP holds potential; its revenue can support high-throughput hydrogen production, and it can substitute for more carbon-intensive CB production methods. The size of the CB market must continue to grow to support significant hydrogen production volumes. As an alternative to CB and its currently limited market, production of larger carbon particles may provide access to applications with substantial market volume.

Graphite and graphite substitutes

Different types of graphite, both natural and synthetic, are valued for their durability and conductivity. Depending on the graphite's classification, it can be used as a critical component of battery and energy storage technology, in aluminum and steel production, and in other industrial applications.[28] Manufacturing of lithium-ion batteries is expected to be the primary driver of graphite demand, with upwards of 500 percent of 2018's annual graphite production required by 2050 for batteries alone.[29]

Natural graphite is mined from rock, with China accounting for 78 percent of global production. The United States, which sources 43 percent of its imported natural graphite from China, produces none.[30] Natural graphite's amorphous, flake, and lump classifications depend on the natural graphite's physical characteristics, each with different purity grades and prices.

Synthetic graphite is produced through an energy-intensive and polluting process of heating petroleum coke or coal tar pitch up to 3000 degrees C for multiple days until it forms a graphite structure.[31] It is generally more pure than natural graphite, with higher consistency and quality. While these factors make it more desirable for battery applications, most of the global production of lithium-ion batteries uses natural graphite due to its favorable cost. In the United States, which does produce synthetic graphite, lithium-ion batteries are generally supplemented with natural graphite.[32] The United States is a net importer of synthetic graphite, with China accounting for 65 percent of the global export market.[33]

Critically for products of MP, "graphite" and "graphitic carbon" are not interchangeable terms. Graphitic carbon refers to highly ordered carbon structures which include graphite, some carbon blacks, carbon nanotubes, and other crystalline forms. If the layers are disordered, the carbon product is better described as amorphous and is likely to have lower conductivity. Beyond terminology, it should not be assumed that a "graphite" or "graphitic carbon" material produced from methane pyrolysis will be fully interchangeable with incumbent graphite applications. MP-produced carbon may exhibit different graphite-like properties that will differ between producers and methods, with some developers describing their carbon as graphite and others as graphite substitutes. Identifying the highest-value use cases will be a largely iterative process between producers and potential customers. Potential markets for these products include steelmaking (which also requires hydrogen), thermal energy storage, batteries, and lubricants, with other potential uses in high-volume, non-graphite markets like concrete and asphalt.[34]

In summary, carbon produced domestically from MP holds potential for replacing imported natural and synthetic graphite if the product is sufficiently similar to graphite's structure and characteristics. MP may also be a cleaner production method for applications where graphitic carbon can substitute for conventional synthetic graphite or other energy-intensive carbon products.

Carbon nanotubes

Carbon nanotubes (CNTs) are cylindrical nanostructures composed of rolled-up graphene sheets. They possess extremely high mechanical strength, electrical conductivity, and thermal stability, making them highly valuable for advanced material applications. Investments in CNTs span a wide range of industries including the semiconductor, energy, and biomedical fields.[35]

CNTs are typically manufactured via chemical vapor deposition (CVD), a production method which functions similarly to methane pyrolysis, i.e., a hydrocarbon gas is injected into a high-temperature reactor with a catalyst, breaking the carbon-hydrogen bonds. As the carbon separates from the gas as a solid, it encapsulates the catalyst to form CNTs. The process has generally been optimized to produce CNTs, for example using acetylene (C_2H_2) instead of methane, with no attention to hydrogen yield. Optimizing the process for hydrogen production permits two streams of revenue, establishing a more robust business model while reducing the cost for both hydrogen and CNTs.

The size of the CNT market is a constraint for the hydrogen product. While CNT applications are positioned to grow as costs decline (e.g., batteries, concrete), even a sizable increase from today's market of approximately 4,300 tons per year would represent very modest hydrogen production amounts, assuming a 3:1 carbon to hydrogen production weight ratio (**Table 4**).

In summary, MP holds potential to significantly scale domestic CNT production and satisfy new CNT market demand in clean energy and energy storage applications.

Challenges

Companies developing MP systems advance through different stages of technology readiness. Each scaled-up design is an exercise in technology de-risking and process optimization. Industry stakeholders largely characterize technology and scaling issues as a solvable part of the innovation process. The most cited barrier to large-scale commercialization is producing a carbon co-product that meets the required properties or specifications to be valuable in carbon product markets. A summary of known challenges includes the following:

Size of carbon product market

Producing a carbon co-product with applications in sizeable markets is a critical prerequisite for companies to succeed commercially. This will likely require both replacing incumbent materials in large-market sectors with low-value carbon and growing the markets for existing high-value carbon applications.

Replacing other materials in large markets (e.g., construction sand and asphalt additives) may provide sufficient demand for MP production of low-value carbon products. While the market sizes of these materials exceed billions of tons globally, it is unclear how competitively priced carbon would affect the economic viability of MP.

For high-value, low-volume products like forms of carbon black and graphite, market growth of existing carbon uses is necessary. Increased demand for battery-grade carbon and high-performance tires may relieve some of those constraints in the near-term but would otherwise be insufficient if MP hydrogen scaled above the low single-digits in market penetration. As noted in **"Carbon Products"**, replacing today's carbon black market alone would only require producing five percent of the world's hydrogen with MP. While difficult to predict, some developers anticipate that high-volume production provided by MP could expand markets by driving down prices and opening advanced carbon products to new applications (e.g., carbon nanotube reinforced materials).

Carbon co-product quality

The physical structure, shape, and characteristics of the carbon product will dictate its applications and value. Reactor designs, conditions (e.g., temperature and formation time), and catalyst selection influence the characteristics of the carbon co-product. As discussed in "**Carbon Products**", simply producing product that could be classified as a specific carbon structure (e.g., carbon black) is insufficient if the product does not meet the specifications required for its integration into tires, batteries, and other potential applications. While standards exist for assessing and classifying some of these carbon products, these standards do not necessarily provide enough information to independently demonstrate suitability for high-grade or proprietary end-use specifications.

Catalyst selection

Catalysts lower the temperature required for methane pyrolysis, influence hydrogen yield, and strongly influence the morphology of the resulting carbon coproducts—sometimes in undesirable ways. Different catalysts vary in their ability to weaken carbon-hydrogen bonds and control how carbon assembles on their surface. Selecting and designing catalysts that promote efficient reactions while resisting degradation under high-temperature conditions is a critical part of research and development.[36] The cost of the catalyst material may also influence selection. For example, two possible catalyst materials, iron ore and nickel, have spot prices of approximately $100 and $15,000 per ton in Q1 2025, respectively.[37] A key challenge is the potential contamination of the extracted carbon product with catalyst residues. For carbon morphologies like filamentous nanotubes, which form around the catalyst itself, post-processing steps may be needed to physically separate the materials. Notably, some companies choose to avoid catalysts altogether to reduce processing issues.

Carbon caking

The formation of solid carbon products can cause issues within the reactor which affect performance and catalyst effectiveness. Carbon particles adhering to surfaces within the reactor (e.g., wall fouling) undermines energy transfer and controlled conditions.[38] This issue can be mitigated by keeping the carbon particles suspended and moving, like in a fluidized or floating reactor, or in a microwave reactor by creating a vortex flow with the injected gas. Carbon buildup also risks catalyst deactivation where carbon formation on the catalyst surface may inhibit further reactions. To address deactivation, some designs may permit for the continuous introduction of additional, relatively cheap (e.g., iron) catalysts that are then extracted alongside the carbon co-product.

Environmental

Economy-wide fossil fuel reduction is critical to mitigating climate change impacts and improving public health. The use of natural gas as a feedstock presents several environmental challenges which must be managed, including supply chain emissions, water consumption, and water pollution.

MP can avoid the combustion or reformation of natural gas into carbon dioxide, which is key to its low lifecycle emissions potential. It is nonetheless critical to properly account for upstream emissions associated with natural gas extraction, processing, and distribution. Methane emissions from these stages are both potent and difficult to quantify, making rigorous monitoring and mitigation efforts a priority to minimize greenhouse gas emissions.

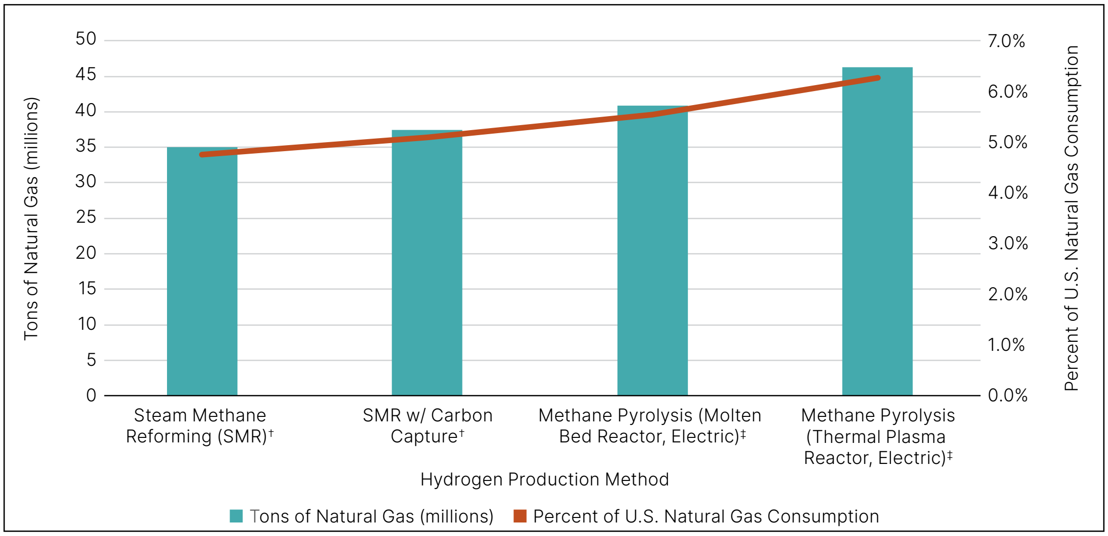
Beyond climate impacts, water consumption and pollution are a significant concern in natural gas production. In 2021, oil and gas operations in the United States generated over one trillion gallons of produced water (i.e., non-potable water from underground reservoirs) containing salts, organic compounds, heavy metals, naturally occurring radioactive materials, and other contaminants.

While most produced water is reinjected for enhanced oil recovery or disposal, more than 12.2 billion gallons of produced water were discharged into water bodies and land surfaces under a patchwork of state and federal regulations. Additional volumes are believed to be lost to spillage.[39]

The dominant practice for extracting natural gas in the United States, hydraulic fracturing, requires several million gallons of freshwater per well sourced mostly from surface water and municipal supplies.[40] Excessive water withdrawal and chemical contamination of drinking water are established risks identified by a 2016 Environmental Protection Agency (EPA) assessment of hydraulic fracturing, which identified limited instances of groundwater pollution while also highlighting significant data gaps and uncertainty in fully studying drinking water impacts.[41]

While MP's use of natural gas provides cost, infrastructure, locational resource advantages, it does present environmental tradeoffs which must be considered and managed. This tradeoff is magnified by MP's higher natural gas usage than SMR, despite its lower lifecycle emissions. For example, replacing 10 million tons of U.S. hydrogen with MP may require 17–32 percent more natural gas than SMR alone (**Figure 9**).

FIGURE 9: NATURAL GAS INPUTS TO PRODUCE 10 MILLION TONS OF HYDROGEN



Natural gas required to produce 10 million tons of hydrogen (current U.S. production) using different hydrogen production methods, inclusive of system energy inputs (e.g., natural gas powering SMR facilities).

† Source data: National Renewable Energy Laboratory 2022[42]

‡ Source data: Shokrollahi et al. 2024[43]

Reducing emissions and environmental impacts along the natural gas value chain is a critical component to demonstrating MP's long-term social license to operate. These environmental challenges should be addressed through a combination of reduced fossil fuel consumption across the economy, strengthened upstream methane leak detection and pollution controls, responsible water resource management, and the continued advancement of a diverse hydrogen production technologies that optimize the use of electricity, water, and natural gas.

Industry Snapshot

The methane pyrolysis (MP) industry is in its early stages, with companies advancing pilot, demonstration, and first-of-a-kind commercial-scale projects to optimize their respective processes and build markets for their carbon products. Projects have garnered interest and investment from governments, chemical and engineering companies, energy suppliers, and materials manufacturers to leverage potential advantages over other hydrogen and carbon production methods.

Technology Developers

The companies leading the development of MP vary in their approaches, employing different reactor technologies, energy inputs, and business models. Examples of pilot and demonstration projects include, but are not limited to, the following:

Thermal Plasma

U.S.-based Monolith operates one of the world's most advanced methane pyrolysis projects in Olive Creek, Nebraska, where it produces hydrogen and carbon black using renewable electricity. The facility uses a thermal plasma reactor to produce up to 4,500 tons per annum (tpa) of hydrogen and 14,000 tons of carbon black materials. In 2023, Monolith and tire company Goodyear announced the first electric vehicle-tuned tire to use carbon black produced from MP.[44] A planned expansion would produce an additional 60,000 tons of hydrogen and 180,000 tons of carbon black while using the hydrogen to produce 275,000 tons of ammonia per year to supply local fertilizer production.[45] In 2021, the Department of Energy Loan Programs Office offered a conditional commitment to guarantee a loan of up to $1.04 billion for the expansion.[46] No loan has been issued as of July 2025.

HiiROC, based in the UK, has developed a thermal plasma torch for a process that the company refers to as "thermal plasma electrolysis," rather than methane pyrolysis. The system uses methane itself as the plasma gas, which the company describes as "splitting by electrolysis," allowing for faster and more complete conversion than using the heat of a typical neutral gas plasma for pyrolysis of methane. The reactor is designed to produce carbon black continuously instead of in batches. The company plans small-scale deployments through 2025 and 2026, with targets to scale up to 10 tons of hydrogen per day by 2027 and 50 tons per day by 2030.

Heated Fluidized Bed

Companies like Graphitic Energy (formerly C-Zero) and Hazer Group have developed fluidized bed reactors, a proven design in other chemical applications, in a scalable and relatively energy efficient process designed to produce a graphitic carbon product.

Graphitic Energy has developed a reactor heated by hydrogen combustion capable of producing a graphitic carbon which may be suited for battery applications. The company's pilot plant in Texas can produce up to one ton of carbon per day (approximately one ton of hydrogen in three days) to obtain scale-up data for commercial plants and provide carbon samples to potential partners. The company plans to commercialize a plant by 2027, which could scale up to 100,000 tpa of hydrogen in a single system.

Hazer Group is an Australian company using an inexpensive iron ore catalyst in its electric-heated reactor to produce graphitic carbon. Having completed its 100 tpa of hydrogen demonstration program in 2024, the company has several projects underway including with FortisBC Energy (Canada) for a 2,500 tpa hydrogen plant which includes CAD 8 million in funding through the provincial government's CleanBC Industry Fund, and with Chubu Electric and Chiyoda for an MP facility in Japan.[47] The company is also working with steelmaker POSCO on integrating into existing steelworks in Korea, and with the U.S. company KBR on the deployment of Hazer's technology in the ammonia and methanol markets with targeted hydrogen facility capacities of 50,000 tpa.

Microwave

Aurora Hydrogen is a Canadian company focused on the hydrogen-side of production while producing a sand-like carbon product that could be used in low-cost, high-volume applications like construction materials and cement.[48] Their production method uses microwave energy combined with a fluidized bed reactor. The company has received $3 million in funding from the Natural Resources Canada Energy Innovation Program and has commissioned a demonstration plant in 2025.[49]

Microwave Plasma

H Quest Vanguard is a U.S.-based company piloting a microwave plasma system designed to produce three tons of carbon black (one ton of hydrogen) per day in a drop-in system the size of a shipping container. The company intends to own, install, and operate the stackable systems to provide on-site hydrogen production for manufacturing plants while relying primarily on revenue from the carbon black. The carbon black product is initially intended for tire tread and energy storage applications, with early product testing suggesting high suitability.

Floating Catalyst Chemical Vapor Deposition

A pilot plant operated by Huntsman Corporation, a global chemical company, is designed to produce 10 tpa of hydrogen and 30 tpa of their carbon nanotube (CNT) product. Huntsman is using its Texas pilot plant to optimize the process with plans to build commercial scale plants with capacities exceeding 1000 tpa of CNT production. The CNT product is the primary revenue focus. The company characterizes the growth of the CNT market as being limited by its currently high price. As CNT production scales to allow for lower prices, the economics may shift from niche applications (e.g., aerospace) to more scalable markets (e.g., EV batteries, tire applications, and concrete).

Thermal, no added catalyst

Modern Hydrogen is a U.S.-based company developing hydrogen-heated reactors. The shipping container-sized systems are designed for modular, distributed, on-site production. The company is testing asphalt applications for its carbon black product with multiple demonstration sites.[50]

Other

Molten Industries is a U.S.-based company targeting the development of large-scale (up to hundreds of tons per day) systems to co-locate with hydrogen customers. The company is currently operating a proof-of-concept design to produce a graphite flake product intended for use in batteries. The company is commissioning a demonstration project with a capacity of 1 ton of hydrogen and 3 tons of carbon per day.

Susteon is a U.S.-based company developing a catalytic reactor using a ceramic structure coated with a conductive carbon layer and iron catalyst. The structure is heated with an electric current to achieve pyrolysis and uses a small amount of carbon dioxide to dislodge solid carbon from the catalyst to avoid deactivation. The company is at the bench-scale stage and expects to build a pilot prototype in the next 1–2 years.

Outlook

MP companies are developing a range of technologies at various production scales with unique business models—all of which will be tested in the coming years.

- **Carbon products:** A common challenge among developers is the need to establish a strong market for their respective carbon products. For high-value materials like CNTs and high-quality carbon black, long-term success requires the market to grow with the volumes MP is capable of supplying. For all materials, including high-volume applications (e.g., tires, asphalt, and concrete), displacing existing products will require meeting stringent quality requirements and standards.
- **Cost competitiveness:** Business models vary widely, ranging from those focused primarily on hydrogen sales to flexible pricing strategies that adjust to market conditions, as well as models that generate revenue exclusively from carbon products. Many companies expect that their production costs will ultimately be competitive with steam-methane reforming (SMR). If their estimates are not realized, success may rely on favorable policies or the willingness of customers to pay a premium for clean hydrogen and sustainably produced carbon products.
- **Scale and distribution:** Companies are pursuing smaller-scale modular systems and large permanent facilities co-located with hydrogen end users. The different scales and reactor designs provide solutions for a range of hydrogen use cases, depending on hydrogen volume and purity requirements. As projects move from pilot to commercial scale, companies will need to demonstrate the reliability and long-term operational capability of their respective designs.

Policy Considerations

Most technologies advancing from the lab and pilot scales to demonstration and early commercial projects are challenged with finding the right kind of support for each development stage. Research and development funding, support for pre-commercial projects, and project financing for capital-intensive scale-ups are roles that the U.S. government has historically filled for technologies important to the public interest.

Once it has reached the point of early commercial adoption, methane pyrolysis (MP) hydrogen production is perhaps the most resilient of the clean hydrogen production pathways to a lack of long-term policy support. However, it remains a challenge in getting to this point, and companies can greatly benefit from government technology innovation institutions and policy. The United States Department of Energy (e.g., Loan Programs Office, ARPA-E, and national laboratory voucher programs), and governments in Canada, Australia, and Germany have provided grants, loans, and other support to aid the advancement of different early-stage MP projects. Given the technology readiness levels, diversity of reactor types, carbon products, and production scales, there is still much to do:

- **Research, development, demonstration, and deployment (RDD&D):** grant and loan support for each project stage of development can accelerate innovation, unlock private capital, and scale domestic production and manufacturing.
- **Production tax credits:** Predictable, long-term, and technology-inclusive tax credits for clean hydrogen and domestic carbon products can drive early production.
- **Support for domestic cleaner hydrogen and carbon products:** Carbon pricing and sector-specific incentives can grow markets for clean hydrogen and carbon products while advancing energy security goals.
- **Curbing methane emissions:** Strong policies to cut natural gas supply chain emissions improve the value and competitiveness of MP.

Strengthening Research and Development (R&D)

Public funding drives breakthrough innovations that may not otherwise be pursued. Early research, lab tests, and pilot-scale projects are critical for high-impact technologies to reach a growth stage toward attracting private-sector funding.[51] Federal support through grants, milestone-based prizes, or collaboration with national laboratories can drive improvements in reactor performance, energy efficiency, and the quality of solid carbon co-products. The Advanced Research Projects Agency for Energy (ARPA-E) has helped to advance several early iterations of methane pyrolysis technologies through its manufacturing research focus area.

In addition to supporting MP systems development, it is equally important to support the development of MP-derived carbon products. Research to assess critical mineral alternatives, like through the Department of Energy's Critical Materials Innovations Hub (CMI), could be leveraged to assess the potential of MP-derived graphitic and carbon nanotube (CNT) products for energy and other critical mineral applications.[52]

Strengthening Development and Deployment

Public-private cost-share grants and loan guarantees attract private investment and expedite the pace of innovation. This kind of support is essential for demonstration-scale and early commercial MP projects to prove out operational reliability, reactor uptime, and carbon product consistency at scale. Development and deployment support should extend to manufacturing facilities to support the domestic production of transportable and exportable reactor systems. Examples of this work includes the Department of Energy's Office of Clean Energy Demonstrations (OCED), which has managed a portfolio of demonstration projects with private sector to bridge the gap between research and deployment, and the Loan Programs Office, which finances innovating large-scale infrastructure projects.

Enabling Early Production with Tax Support

Production-based tax credits are a powerful incentive to scale domestic production of clean hydrogen while technology and cost efficiencies develop. Well-structured production tax credits reduce financial risk and attract private capital for companies to scale technologies that would otherwise be sidelined by short-term cost disadvantages. Proper implementation requires stable policy conditions and inclusiveness to new technology pathways.

In the case of the federal 45V Credit for Production of Clean Hydrogen (or successor credits), lifecycle accounting methodologies which determine credit eligibility should be maintained to include and accommodate MP pathways (currently omitted from the 45VH2-GREET model).[53] Ensuring inclusivity of clean hydrogen incentives maintains a level playing field for MP as an emerging hydrogen production pathway that may offer lower costs, higher scalability, and greater emission reduction potential sooner than other pathways. Alternatively, MP's production of solid carbon products should be considered in the context of production credits. For example, utilization or sequestration of solid carbon could be considered in a revised version of the 45Q Credit for Carbon Oxide Sequestration, which was written to apply only to carbon oxides. Credits for advanced manufacturing (e.g., battery components) may also prove relevant to MP, depending on the product type.

Incentivizing Domestic Use and Procurement of Cleaner Hydrogen and Carbon Products

Demand for clean hydrogen requires effective market signals. To date, the weakness of these market signals has been a major barrier in the development and deployment of clean hydrogen technology. This is largely attributable to clean hydrogen's primary value-add, emissions reductions, lacking market recognition proportional to the environmental, societal, and economic benefits of reducing global greenhouse gas pollution. Combining a carbon pricing program with targeted demand-side incentives would accelerate MP's development.

An economy-wide market-based carbon pricing program would strengthen market signals for both the hydrogen and carbon products produced by MP. Carbon pricing programs like a carbon tax or cap-and-invest program provide a predictable framework which provides emitters with the flexibility to find the lowest-cost options for reductions. For current users of steam-methane reforming (SMR) or autothermal reforming (ATR) hydrogen, or emissions-intensive products like carbon black, the development of MP may provide a cost-effective option.

Supplementing an economy-wide carbon pricing program with targeted demand-side incentives would accelerate uptake in key sectors. Federal programs that offer industrial decarbonization grants or incentives for fuel switching can help overcome initial capital barriers to sustain demand for clean hydrogen in hard-to-abate sectors. The federal Climate Pollution Reduction Grants program, for example, is designed to support sub-national programs such as RISE PA, a grant program for Pennsylvania's industrial facilities to reduce pollution and greenhouse gas emissions.[54] State-provided incentives like Colorado's Industrial Tax Credit and California's INDIGO program further support industrial projects that deploy greenhouse gas mitigation technologies and practices.[55]

Similarly, targeted policy support of MP carbon products will help displace more polluting products like conventional carbon black. Developing industrial emission targets or manufacturing performance standards would reward producers and buyers of cleaner carbon products to stimulate demand in applications like tires. Procurement incentives or federal purchasing commitments for domestically produced battery-grade carbons could bolster domestic supply chains and reduce reliance on imported materials and mining. Supportive market demand for these materials would improve the economics of MP's early deployment while supporting national goals around energy security and clean manufacturing.

Addressing Methane Emissions to Maximize Climate Benefits

Methane is a powerful greenhouse gas and minimizing upstream emissions is essential for any hydrogen pathway reliant on natural gas. This is particularly the case for MP systems, where upstream emissions may contribute most of the emissions for the entire system. Policies that incentivize methane emissions reductions, through regulatory limits, leak detection programs, or methane performance standards can help MP deliver meaningful climate benefits. Aligning methane policy with hydrogen production incentives would send a clear signal that only low-emissions supply chains will qualify for incentives under the clean hydrogen economy.

Conclusion

Methane pyrolysis represents a promising and versatile addition to the portfolio of clean hydrogen production technologies. Its ability to generate hydrogen without direct carbon dioxide emissions, coupled with the potential to produce valuable solid carbon co-products, offers a dual-revenue pathway that could enhance economic resilience and scalability. While still at early stages of commercialization, MP benefits from modularity, broad siting flexibility, and reduced water and energy demands compared to other clean hydrogen pathways. However, realizing MP's full potential will require further advancements in reactor design, carbon product quality, and supportive policy frameworks—particularly recognition under federal clean hydrogen incentives. With targeted public support and ongoing private-sector innovation, MP could become a vital component of the clean hydrogen economy, contributing to U.S. decarbonization goals and clean manufacturing leadership.

Appendix: Methane Pyrolysis Designs

The following list describes reactor types for methane pyrolysis using designations commonly found in the literature. These terms are not universal or standardized and multiple reactor types may overlap. These terms are intended to provide a general sense of the design approach and/or the energy delivery mechanism.

Catalytic Thermal Pyrolysis (i.e., Thermocatalytic)

Thermocatalytic methods apply heat in the presence of a catalyst which serves to lower the energy required to break methane's carbon-hydrogen bonds.

The benefit of using a catalyst is the ability to achieve pyrolysis at temperatures of 700-900 degrees C instead of over 1000 C. This not only reduces energy requirements but also mitigates the need to incorporate expensive materials that can withstand and operate at extreme temperatures. In some cases, the catalyst may assist in forming the desired carbon product.

The use of a catalyst does add complications. Catalysts can "deactivate" if carbon builds up on its surface. Catalyst can also degrade or get removed with the carbon product, thereby requiring a continuous feed of new catalyst material into the reactor. Comingling of catalyst with the carbon product also presents "catalyst contamination" issues, whereby the extracted carbon product contains traces of the catalyst that alter the quality of the product.

Molten catalyst reactors

Methane is introduced into a molten mixture containing catalysts, such as nickel and/or bismuth.[56] As methane bubbles through the molten mixture, it splits into hydrogen and solid carbon. The hydrogen is captured and the carbon product floats to the surface where it can be removed. This method can be effective in avoiding catalyst deactivation but lab-scale results may be more difficult and expensive to reproduce at larger scales.

Fluidized bed reactors

Methane is introduced into a high-temperature mix of solid (e.g., sand-like) metal catalysts, such as iron or nickel.[57] The flow of the methane mixes and suspends the solid mixture, creating a churning "fluidized" state within the reactor. The approach is designed to ensure efficient heat and mass transfer while supporting high-temperature reactions. Systems may be designed to support continuous introduction of more catalyst material, while the spent carbon/catalyst mix is extracted to maintain reaction efficiency. The choice of catalyst can change the morphology of the carbon products.

Floating catalyst reactor

A vaporized catalyst precursor (e.g., ferrocene) is injected into the reactor with methane. The precursor decomposes in the heat of the reactor to form a floating catalyst (e.g., iron nanoparticles). The carbon formed wraps around and encapsulates the floating catalyst as a carbon nanotube. Once collected, the carbon product can be processed to either mechanically remove the catalyst from the carbon nanotube or leave the catalyst as part of the product, depending on the application.

Structured catalyst reactor

Methane is introduced into a reactor containing an embedded catalyst structure. The structure is made of a solid material (e.g., ceramic honeycomb design) that is coated with a conductive material that allows it to be heated as electric current is applied. The coating also contains a catalyst that enables pyrolysis when methane is passed through the heated assembly.

Non-Catalytic Thermal Pyrolysis

Temperatures of well over 1,000 degrees C are reached to achieve pyrolysis without the use of a catalyst. The higher temperatures require significant energy inputs and the need for materials to withstand the high temperatures on a commercial scale. The lack of catalysts avoids issues related to catalyst deactivation and contamination of the carbon product.

Moving bed reactor

The walls of a moving bed reactor are heated (e.g., with electricity). Carbon particles are fed into the top of the reactor as methane is introduced from the bottom to create a counterflow. Newly generated carbon from the thermal pyrolysis accumulates on the introduced carbon particles and drops to the bottom of the reactor for collection. The hydrogen product cools and is collected from the top.[58]

Plasma Pyrolysis

Plasma forms when a neutral gas is energized enough for electrons to be stripped from atoms, creating a mix of charged and uncharged particles. The energy in plasma can be used to excite methane molecules into pyrolysis.

Thermal plasma reactors

A high-voltage electric current is passed through a neutral gas (e.g., nitrogen) to form a plasma torch that can approach temperatures of up to 10,000 degrees C. Methane introduced into the reactor is superheated to rapidly produce hydrogen at a very high conversion rate without the need for catalysts. The nature of the reactor allows for a highly tunable process which may provide for greater control over the quality and consistency of the carbon product. The process is highly energy-intensive and requires significant electricity inputs to maintain the high temperatures. For this reason, thermal plasma reactors may be best suited for large-scale applications where the energy costs can be offset by the reaction's higher conversion rates. Reactor designs must also use materials that can withstand the extreme heat while maintaining operational stability.[59]

Non-thermal plasma reactors

The main difference between thermal and non-thermal plasma (NTP) reactors is energy distribution. Thermal plasma creates a uniform high temperature across particles in the plasma. With non-thermal plasma, the temperature of the high-energy electrons is significantly higher than that of the gas particles present in the reactor.[60] Using this method, the high-energy electrons break methane's carbon-hydrogen bonds. The speed of the reaction with NTP is faster than thermal pyrolysis methods, which can assist with avoiding carbon product buildup and support continuous operations. Reactor design and tuning (e.g., gas flow rates and power input) impact conversion rates and the carbon product. This method may be particularly suitable for smaller-scale applications or when targeting specific carbon products.

Microwave plasma reactors

Microwave plasma is generally categorized as a non-thermal plasma but warrants its own description due to its distinct characteristics. These reactors utilize rapidly oscillating electromagnetic fields to accelerate electrons. The high-energy electrons then heat the gas directly through repeated collisions with atoms and molecules. The electromagnetic fields are most commonly produced using magnetrons similar to those found in microwave ovens, though alternative types of generators (e.g., solid-state devices and klystrons) may be used to achieve different levels of precision or power. While early microwave plasma systems were constrained by requiring low-pressure operation and non-conductive materials to contain the plasma (i.e., dialectic containment), modern designs overcome these issues. As the energy is deposited directly into the methane gas and not the reactor walls, more cost-effective materials like steel and aluminum can be used in the reactor's construction. The process produces tunable carbon products depending on the reactor configuration, and the absence of a catalyst makes it particularly well-suited for high-throughput production of carbon black without catalyst contamination. Limitations in microwave power scalability (approximately 100 kW of output power per magnetron generator) currently favor applications in the 100-400 kW range per unit composed of multiple generators.[61] With potential efficiencies of approximately 12 kWh/kg of hydrogen, these units are better suited for small scale distributed hydrogen production or systems that can be modularly scaled to larger outputs.

Microwave Pyrolysis

Microwave Reactors

While microwave reactors also use a magnetron to convert electricity into electromagnetic waves, they are distinct from microwave plasma reactors due to the nature of energy transfer. Instead of heating the gas directly, microwaves are absorbed by another receptor or catalyst particle (e.g., carbon or a metal ore). The microwaves heat the catalyst particles, which then heat the methane gas. The presence of the catalyst also reduces the temperature required to achieve pyrolysis. Microwave pyrolysis and microwave plasma reactors face the same scalability constraints with respect to magnetron power output.

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