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# Natural Gas Pyrolysis

## A Bridge to a Green Hydrogen Economy

**Aashwij Prabhu, Hemant Mallya and Sabarish Elango**

Issue Brief | January 2023

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**The Council's current initiatives include**: A go-to-market programme for decentralised renewable energy-powered livelihood appliances; examining country-wide residential energy consumption patterns; raising consumer engagement on power issues; piloting business models for solar rooftop adoption; developing a renewable energy project performance dashboard; green hydrogen for industry decarbonisation; state-level modelling for energy and climate policy; reallocating water for faster economic growth; creating a democratic demand for clean air; raising consumer awareness on sustainable cooling; and supporting India's electric vehicle and battery ambitions. It also analyses the energy transition in emerging economies, including Indonesia, South Africa, Sri Lanka and Vietnam.

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Natural gas pyrolysis can be quickly scaled up to create a market for green hydrogen.

Image: iStock

# Executive summary

India currently consumes approximately six million tonnes (Mt) of hydrogen per year (Lee 2021). Hydrogen production presently relies on steam methane reformation (SMR) of natural gas, a process whose main by-product is $CO_2$. With the *National Green Hydrogen Mission* (NGHM), India intends to shift away from this 'grey' hydrogen while reducing the economy's dependency on fossil fuels by introducing green hydrogen. There is also the intent to incrementally blend green hydrogen with natural gas. These initiatives are expected to increase the demand for hydrogen (Ministry of Petroleum & Natural Gas [MoPNG] 2021a).

## A. Green hydrogen is currently expensive

Green hydrogen is produced by splitting water into hydrogen and oxygen using renewable electricity. However, the development of the green hydrogen ecosystem is expected to take time, possibly over a decade, due to its high cost, the need for large-scale GW-level deployment of renewable power sources, and massive capital investments. While grey hydrogen currently costs approximately 1.6–1.7 USD/kg $H_2$ (for a natural gas price of 8 USD per million British thermal units (MMBtu), green hydrogen is estimated to cost 4–5 USD/kg $H_2$ (Biswas, Yadav, and Baskar 2020). However, the development of the hydrogen ecosystem need not rely only on green hydrogen. Hydrogen production through pyrolysis of natural gas can be considered a transition pathway to accelerate the transition to a green hydrogen–based economy. Currently, hydrogen produced through natural pyrolysis is significantly cheaper than green hydrogen and produces 85 per cent lower emissions from the production process than SMR.

## B. Turquoise hydrogen can play a bridge role

Natural gas pyrolysis entails the decomposition of the methane in the gas into hydrogen and solid carbon at high temperatures. The solid carbon by-product can be sequestered more easily than the gaseous $CO_2$ from SMR. The solid carbon can potentially be used as a substitute for carbon-based inputs in other industrial processes. Further, newer technology modifications to the pyrolysis process generate new-age materials such as carbon nanotubes and graphite as by-products, which are essential for the green energy transition, due to their use in various applications such as batteries and fuel cells.

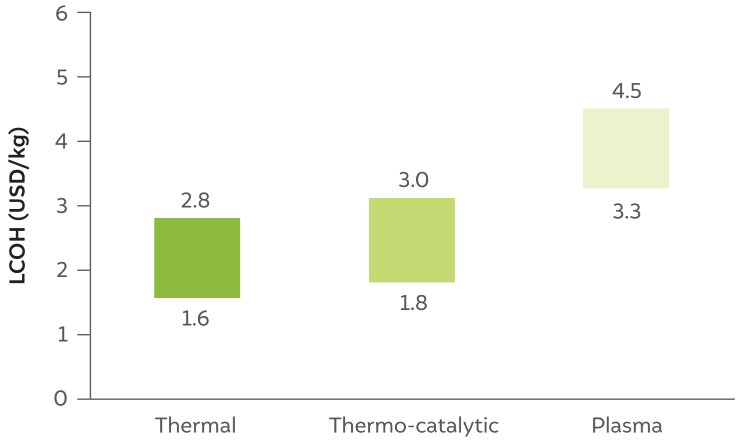
## C. Turquoise hydrogen from pyrolysis can be produced at favourable prices

To understand the economics of natural gas pyrolysis in India, we estimated the cost of hydrogen produced through three natural gas pyrolysis pathways – thermal pyrolysis, thermo-catalytic pyrolysis, and plasma pyrolysis. As shown in Figure ES 1, the thermal pyrolysis process has the lowest levelised cost of hydrogen (LCOH) among the three, at 2.8 USD/kg $H_2$, without any value attributed to the by-product. If the by-product carbon can be sold at 0.4 USD/kg, then the LCOH reduces to 1.6 USD/kg $H_2$. The thermo-catalytic process has a slightly higher LCOH, but it affords better control of the morphology of the carbon by-product. While our cost comparison considers the price of carbon black, by-products with better morphologies (such as graphite) can be obtained through thermo-catalytic pyrolysis. Higher quality by-products can fetch a significantly higher price than carbon black, thus potentially resulting in a lower LCOH than that of thermal pyrolysis. The plasma pyrolysis process is the most expensive among the three technologies, but since it requires only electricity as an energy source (as opposed to using natural gas for heating as for the thermal and thermo-catalytic processes), the process emissions can be negated using renewable power.

A comparison of the LCOH for the different processes is shown in Figure ES 2. Green hydrogen produced through electrolysis is expected to become cost-competitive with turquoise hydrogen only after 2030. Grey hydrogen from SMR has an LCOH of approximately 1.6–1.7 USD/kg $H_2$ but produces much higher emissions. Further, turquoise hydrogen could be made even cheaper if higher-value carbon by-products are produced. Hydrogen produced using SMR with carbon capture and sequestration (CCS), i.e., blue hydrogen (which is more comparable from an emissions standpoint), would have an LCOH of almost 2.7 USD/kg $H_2$ (interpolated from Biswas, Yadav, and Baskar 2020). However, there are currently no CCS facilities operational in India, and it will take several years for the infrastructure to be built.

> **Natural gas pyrolysis entails the decomposition of the methane in the gas into hydrogen and solid carbon at high temperatures.**

**Figure ES1** **Thermal pyrolysis provides the lowest LCOH among all the available technologies**

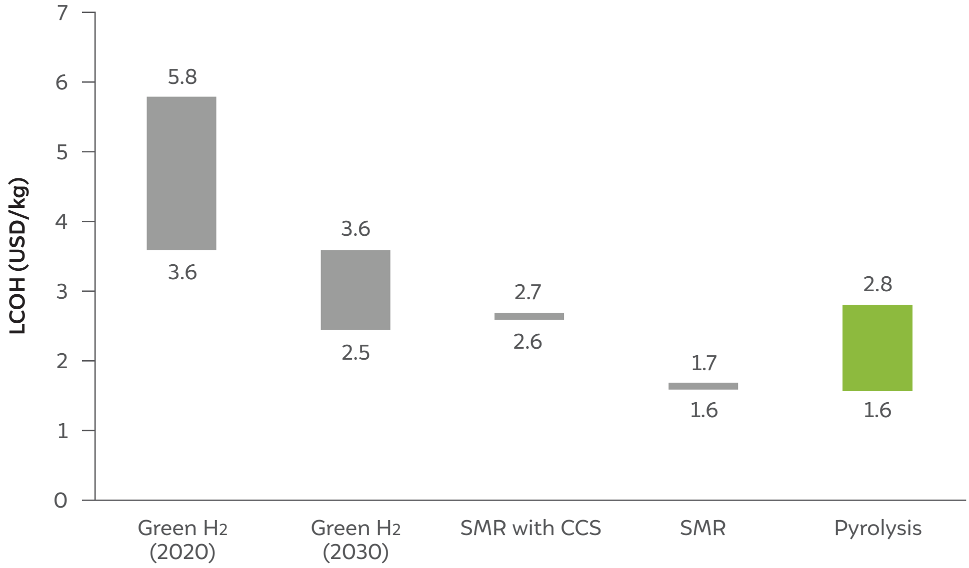



*Source: Authors' analysis*

Note:

1. The price range corresponds to carbon by-product selling price of 0.40 USD/kg to 0 USD/kg
2. Natural gas price assumed to be 8 USD/MMBtu
3. The LCOH from plasma pyrolysis assumed the use of a domestically sourced electron accelerator. If imported, the LCOH increases by 4–5 USD/kg

**Figure ES2** **Hydrogen from natural gas pyrolysis is cheaper than hydrogen from electrolysis and comparable with SMR with CCS**




*Source: Authors' analysis; Biswas, Yadav, and Baskar (2020)*

Note:

1. The range of green hydrogen costs depends on the choice of an alkaline (cheaper) or polymer electrolyte membrane (costlier) electrolyser.
2. The SMR and pyrolysis LCOH are shown for a gas price of 8 USD/MMBtu. The upper and lower bounds for SMR depend on operational characteristics and capacity utilisation. The upper and lower bounds for pyrolysis depend on the selling price of the carbon by-product.

## D. Pyrolysis has its own challenges

Utilising natural gas to produce hydrogen brings its own set of challenges in terms of price and natural gas and methane emissions from natural gas systems. However, these challenges can be mitigated to a large extent. Recently, LNG spot market prices hit a record high and have been hovering at over 30 USD/MMBtu, calling into question the economic feasibility of natural gas pyrolysis. Our analysis shows that even when the average crude oil price stood at 90 USD per barrel (Bbl) in the fourth quarter of 2021–22 (Trading Economics 2022), the landed price of LNG in India was approximately 14.2 USD/MMBtu (spot + long-term contract purchases) (Department of Commerce 2022), which will yield turquoise LCOH competitive with green hydrogen today. Besides, fossil fuel prices are cyclical – the average gas price for the last decade was only 8.3 USD/MMBtu (MoPNG 2022, MoPNG 2016). Hence, long-term LNG contracts should largely mitigate fluctuations in natural gas prices.

Natural gas systems release methane emissions that are over 29.8 times more potent than carbon dioxide (ERCE 2021). There is a concern that pyrolysis will lead to increased consumption of natural gas and thus lead to an increase in methane emissions. However, there are known technologies and practices that can be utilised to mitigate methane emissions. Initiatives such as the Oil and Gas Methane Partnership, country-level pledges such as the Global Methane Pledge, and natural gas supplier certifications for low-methane supplies should alleviate the issue of methane emissions. Further, there is a trade-off between the land and water impacts (and consequently, ecological impact) of producing green hydrogen (due to the water needed for electrolysis and land needed for RE) which needs to be weighed against the impact of methane emissions from natural gas systems.

## E. Recommendations to scale-up pyrolysis as a short-to-medium-term solution

Regardless of the challenges, natural gas pyrolysis is a promising solution due to its price and emissions advantages compared to green and grey hydrogen respectively. Hence, we make the following recommendations for its consideration as a short-to-medium-term bridging solution to develop the hydrogen economy (until green hydrogen is commercialised).

> **Natural gas pyrolysis is a promising solution due to its price and emissions advantages.**

i. **Scale up the hydrogen economy** by accommodating turquoise hydrogen in purchase obligations until affordable green hydrogen is available at scale. Limited pyrolysis capacity can still supplement green hydrogen supply after the latter is commercialised, especially during off-peak hours for renewable energy.

ii. **Carry out a pilot study** to estimate the feasibility of hydrogen production through natural gas pyrolysis at a suitable location with natural gas availability and potential offtakers of hydrogen and carbon. Thermal pyrolysis is the least expensive option in our analysis; thermo-catalytic and plasma pyrolysis could become more affordable as the technology matures and is deployed at scale. Further, higher value carbon by-products can be produced with thermo-catalytic pyrolysis. Therefore, all three technologies can be piloted to identify the best option for India.

iii. **Blend turquoise hydrogen with natural gas** to incrementally decarbonise the natural gas demand base. Deploying pyrolysis plants (of 95 ktpa $H_2$ capacity each) near seven existing pipeline injection points (LNG terminals and gas processing sites) could offer the opportunity to seamlessly blend 15 per cent of hydrogen by volume. This would involve a total capital investment of USD 318 million for a plant at each of the 7 major aforementioned natural gas injection points.

iv. **Convert existing pyrolysis plants** to use natural gas. Pyrolysis technology is currently used to produce carbon black – a material used in the manufacture of rubber products (mainly tyres, dyes, pigments, etc.). However, existing pyrolysis plants primarily use low-value residual oils to produce carbon (Birla Carbon n.d., PCBL 2021). These plants could possibly switch to natural gas without significant investment.

v. **Leverage new and existing markets** for carbon by-products to offset the price of hydrogen. Carbon from pyrolysis can be used to supplement the domestic supply of carbon black. It could potentially substitute coke in blast furnaces for producing steel. If all the carbon from the seven aforementioned pyrolysis plants were used for steel-making, more than USD

500 million worth of coking coal imports could be avoided, as carbon from pyrolysis can be sold at a lower cost than blast furnace coke. The carbon can also be used to produce carbon electrodes for the manufacture of aluminium. Another potential pathway is the production of activated carbon from carbon black. Carbon black can be used in the manufacture of sodium-ion batteries, while graphite can be used in lithium-ion batteries.

# 1. Introduction

India consumes approximately six million tonnes of hydrogen per annum across several energy-intensive industries, primarily refineries and the fertiliser industry (Lee 2021). The hydrogen consumed today is produced through steam-methane reformation (SMR) of natural gas, which produces significant amounts of greenhouse gas (GHG) emissions. The Government of India has announced the *National Green Hydrogen Mission* (NGHM), which proposes blending green hydrogen with the incumbent fuels and feedstocks of various sectors such as fertiliser, refinery, and natural gas pipeline systems (Ministry of Petroleum & Natural Gas [MoPNG] 2021a).

## 1.1 Green is much more expensive than grey hydrogen

Green hydrogen is produced through the electrolysis of water using renewable power and has zero direct emissions. However, the price of green hydrogen (4–5 USD/kg $H_2$) is expected to be uncompetitive with grey hydrogen produced using the SMR process (1.5–1.8 USD/kg $H_2$) for at least a decade (Biswas, Yadav, and Baskar 2020). According to our estimates, blending 15 per cent green hydrogen by volume with natural gas will increase the delivered price of natural gas by nearly 30 per cent. Therefore, cheaper alternatives are needed in the interim, until green hydrogen prices reduce. Though grey hydrogen is cheaper, it has a high carbon footprint of 8–12 kg $CO_2$/kg $H_2$ (Blank and Molly 2020). Further, the price of grey hydrogen is vulnerable to a certain extent to fluctuations in the price of imported natural gas. However, most of India's gas imports are secured under long-term contracts that have price ceilings; thus, the exposure to volatile spot prices is fairly limited.

## 1.2 Blue hydrogen is not a short-term solution

Reducing the carbon footprint of SMR using carbon capture and sequestration (CCS), i.e., blue hydrogen, would increase the price of hydrogen by at least 1 USD/kg $H_2$ (Biswas, Yadav and Baskar 2020). However, apart from the cost increase, CCS is not an option in the short and medium term as there are no active sequestration sites in operation in India. In fact, no geological sites have even been identified for potential sequestration other than one producing oil and gas reservoir – ONGC Gandhar, in the state of Gujarat (BusinessWire 2022a) – for enhanced oil recovery operations. Hence, blue hydrogen through the CCS route in India could take many years, if not decades.

**Table 1** The different colours of hydrogen

| Colour of hydrogen | Technology | Feedstock/electricity source | GHG footprint |
|---|---|---|---|
| **Green hydrogen** | Water electrolysis | Wind, solar, small hydro, geothermal, tidal | Minimal |
| **Purple/pink hydrogen** | | Nuclear | |
| **Yellow hydrogen** | | Mixed-origin grid electricity | Medium |
| **Blue hydrogen** | SMR/coal gasification with CCS | Natural gas, coal | Low |
| **Turquoise hydrogen** | Pyrolysis | Natural gas | Low |
| **Grey hydrogen** | SMR | | Medium |
| **Brown hydrogen** | Coal gasification | Brown coal (lignite) | High |
| **Black hydrogen** | | Black coal | |

*Source: Authors' adaptation of Global Energy Infrastructure (2021)*

### 1.3 Turquoise hydrogen can play the bridge role

Developing a green hydrogen economy will require significant offtake by end-users, supply chain establishment, and overall ecosystem development, all of which cannot happen quickly if the price of green hydrogen does not decrease substantially. However, the price of green hydrogen cannot decrease without substantial scale. This conundrum can be addressed by utilising turquoise hydrogen produced through natural gas pyrolysis as a short-to-medium term solution. This process allows the production of hydrogen at a low price, comparable to grey hydrogen, but offers environmental benefits closer to green hydrogen.

In the pyrolysis process, natural gas is heated to a high temperature to split methane, which is the primary component of natural gas, into hydrogen and solid carbon. Solid carbon is easier to sequester or use than gaseous carbon dioxide. Additionally, the carbon footprint of the pyrolysis process can be as low as 1.8 kg $CO_2$eq/kg $H_2$ depending on the type of pyrolysis pathway and source of reaction energy (i.e., if the by-product solid carbon is sequestered or finds use in non-combustion applications) (CertifHy 2021; Parkinson et al. 2018).

## 2. Pyrolysis: a review

The natural gas pyrolysis process has been around since the 1980s (see Annexure for more information). Conventionally, natural gas pyrolysis involves heating the feedstock to above 1,000°C to split the methane molecule into hydrogen and carbon, as shown in Figure 2. The primary objective is to extract the maximum amount of carbon black, which is a saleable commodity with applications in the rubber industry. Technological improvements in recent years allow better conversion rates and lower operating temperatures such that the primary objective is to increase hydrogen output. Current pyrolysis technologies can be classified into the following.

i. Thermal pyrolysis

ii. Thermo-catalytic pyrolysis

iii. Plasma pyrolysis

### 2.1 Technology overview

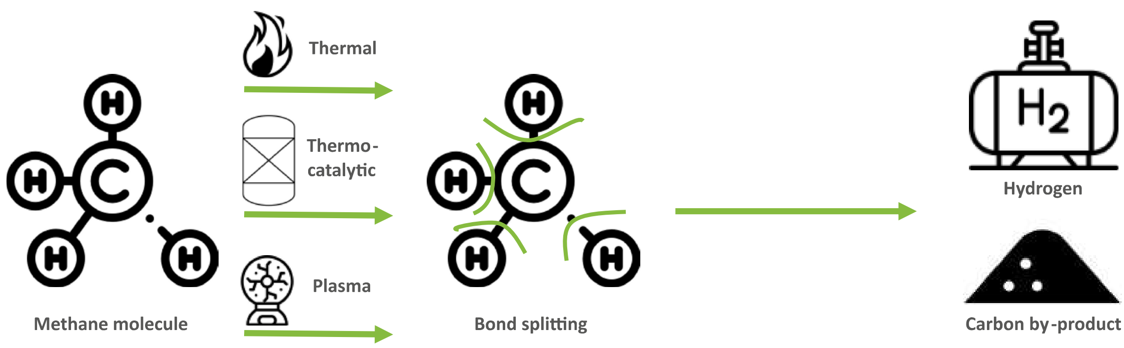
The different pyrolysis technologies differ mainly in the way heat is delivered to the process. Thermal pyrolysis is a more conventional process, whereas thermo-catalytic and plasma pyrolysis are newer. An overview and a comparison of the three pyrolysis technologies are provided in Table 2. More information regarding the different companies developing pyrolysis technologies, their current readiness levels, and other parameters is given in the Annexure.

### 2.2 A comparison of greenhouse gas emissions

The key motivations for using natural gas pyrolysis are lower greenhouse gas emissions compared to the traditional SMR pathway and the lower price compared to green hydrogen. A comparison of the carbon intensity of energy from natural gas pyrolysis and other alternate hydrogen production pathways (SMR, SMR with CCS, and coal gasification) is provided in Table 3.

Plasma pyrolysis is the most energy-intensive of the three technologies. However, since it uses electricity for heating, it can operate without any process emissions if the electricity is from a renewable source. The thermal and thermo-catalytic processes rely on the combustion of natural gas to provide heat, thus leading to some process emissions.

**Figure 1** Natural gas (methane) pyrolysis produces solid carbon as a by-product with no greenhouse gas emissions




*Source: Authors' illustration*

**Table 2** A comparison of natural gas pyrolysis pathways

| Parameters | Thermal pyrolysis | Thermo-catalytic pyrolysis | Plasma-based pyrolysis |
|---|---|---|---|
| Operating temperature | 1,100–2,000°C | 800–1,000°C | <1,000°C (cold plasma)<br>–>1,000°C (hot plasma) |
| Process description | Direct decomposition of methane using a heat source, which could be natural gas, recycled hydrogen, or other renewable fuels. | Decomposition of methane in the presence of a catalyst, which may be carbon or a certain transition metal at a relatively lower temperature. | A plasma generator (non-thermal sources: microwave, dielectric barrier discharge or electron beam; thermal sources: electric arc) is used to deliver an enormous amount of energy in a short span to decompose methane molecules. |
| Advantages | No novel or proprietary equipment is required. | Decreased utility costs due to comparatively lower operating temperatures. The desired carbon allotrope can be obtained based on the catalyst and temperature. | High one-pass-conversion rates with high hydrogen purity. Can use renewable electricity to provide process energy. |
| Disadvantages | High operating temperatures can cause equipment degradation and increased utility costs. May require the use of fossil fuels (natural gas) for heating. No control over the allotrope of the carbon by-product. | Catalyst deactivation may be caused by soot formation; clearing soot by burning emits $CO_2$. Uses some natural gas for heating. Availability of the catalyst material in adequate quantities may be a concern. | Hard to source high-power plasma generators. The largest electron accelerator currently operational is rated at 560 kW (Chmielewski 2011). Very capital-intensive. |
| Specific energy; feedstock + fuel (MJ/kg $H_2$) | 21.4 (from natural gas) | 14.8 (from natural gas) | 7.8 (from grid electricity) |
| Carbon footprint (kg $CO_2$eq/kg $H_2$) | 2.2 | 1.8 | With GEF = 6.1<br>With RE = 0.0 |

*Source: Keipi, Tolvanen, and Konttinen 2018; Parkinson et al. 2017; Lane and Spath 2001; Parkinson et al. 2018; Kerscher et al. 2021; Upham et al. 2017; Palmer et al. 2020*

Notes:
1. The carbon footprint for pyrolysis assumes that the carbon by-product is either sequestered or used for non-combustion applications.
2. For plasma pyrolysis, we considered India's grid emission factor (GEF), which is 0.7 kg$CO_2$eq/kWh (Carbon Footprint 2020).

One of the options being explored currently is to continue using SMR to produce hydrogen but to sequester the carbon dioxide underground; this is referred to as blue hydrogen. The emissions footprint of blue hydrogen is lower, but it is not perfectly zero because not all of the carbon dioxide emissions can be captured. Even with carbon sequestration, the thermal and thermo-catalytic options have a significantly lower footprint than SMR with CCS. Plasma pyrolysis has a marginally higher emissions footprint compared to blue hydrogen as its emissions footprint is dependent on that of the power grid.

To optimally minimise the emissions footprint, the solid carbon produced through pyrolysis should be sequestered. In the absence of adequate sequestering measures, the solid carbon, typically in the form of carbon black, can be utilised as a fuel. Even if the by-product carbon from pyrolysis is combusted for energy, the GHG emissions of pyrolysis will still be lower than that of SMR (per GJ of energy output) and coal gasification (per kilogramme of hydrogen produced). Assuming that the carbon by-product is used for combustion downstream, the emissions intensity of thermal and thermo-catalytic pyrolysis per kilogramme of hydrogen produced is marginally higher than SMR. Operationally, pyrolysis provides a distinct advantage over blue hydrogen as underground $CO_2$ sequestration is an expensive affair, and there are very few commercially operational underground sequestration sites across the world.

**Table 3** The carbon intensity of pyrolysis is significantly lower than SMR

| Colour of hydrogen | Process | GHG emissions intensity | |
|---|---|---|---|
| | | kg $CO_2$/GJ | kg $CO_2$/kg $H_2$ |
| Turquoise hydrogen | Thermal pyrolysis | 18.3 | 2.2 |
| | Thermo-catalytic pyrolysis | 15.0 | 1.8 |
| | Plasma pyrolysis | With GEF = 51.2<br>With RE = 0.0 | With GEF = 6.4<br>With RE = 0.0 |
| | Thermal pyrolysis<br>(with downstream combustion of the carbon by-product) | 62.9 | 13.2 |
| | Thermo-catalytic pyrolysis<br>(with downstream combustion of the carbon by-product) | 61 | 12.8 |
| | Plasma pyrolysis<br>(with downstream combustion of the carbon by-product) | With GEF = 81.6<br>With RE = 44.4 | With GEF = 17.1<br>With RE = 52.4 |
| Grey hydrogen | SMR | 91.7 | 11.0 |
| Blue hydrogen | SMR with CCS | 47.5 | 5.7 |
| Black hydrogen | Coal gasification | 165.3 | 20.0 |

*Source: Authors' analysis; SMR (Blank and Molly 2020); SMR with CCS (Howarth 2021); coal gasification (authors' analysis)*

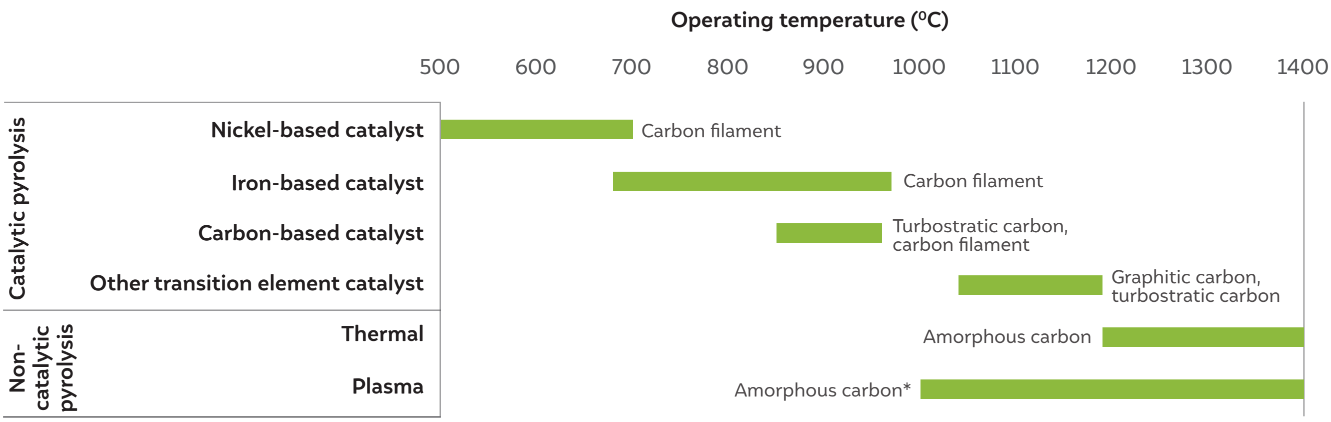
Note: GEF – grid emission factor; RE – renewable electricity

## 2.3 By-products of natural gas pyrolysis

The allotrope of the by-product carbon formed along with hydrogen depends on the operating conditions and the catalyst. Figure 3 shows the carbon products formed at different temperature ranges and for various catalysts. Since thermal pyrolysis occurs at high temperatures (above 1,000 °C), the by-product carbon is in the form of amorphous carbon, a low-grade allotrope. Amorphous carbon is nothing but solid carbon black, which is currently used as a filler in rubber products such as tyres. Carbon black increases the strength of rubber and provides protection from ultraviolet radiation and ozone.

When thermo-catalytic pyrolysis is used, the deposited carbon possesses chemistries varying from turbostratic and graphitic carbon (intermediate to amorphous and crystalline carbon) to high-quality carbon filaments. At sufficiently high temperatures, turbostratic carbon spontaneously converts to graphite through

**Figure 2** Achieving higher quality carbon by-products requires catalysts



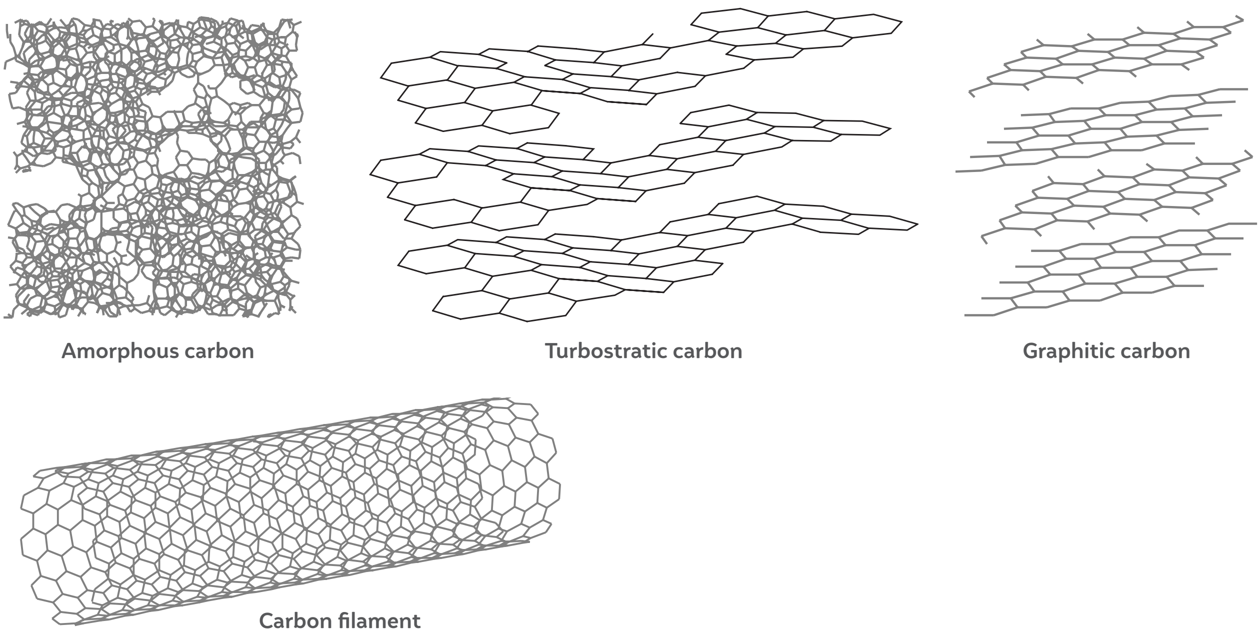

*Source: Authors' adaptation from Muradov and Veziroğlu (2004)*

Notes:
1. The text in the chart indicates the carbon morphology expected for that temperature.
2. *Conventional high-temperature natural gas pyrolysis results in amorphous carbon with the exception of Transform Materials' technology, which produces acetylene as the main product and hydrogen as a by-product.

graphitisation (Chung 2021; Ruz 2016). Conventionally, graphite is used to manufacture stationery, lubricants, refractories, paints, and batteries and in nuclear reactors (Schulz et al. 2017).

Understanding the allotrope of the carbon produced is essential in cases where the carbon is to be utilised and must be of a specific quality. The choice of technology and the associated by-product is vital from a cost perspective. As can be observed, thermo-catalytic pyrolysis produces by-products that have high value, primarily carbon fibre filaments and potentially carbon nanotubes. Hence, it caters to a growing market for lightweight advanced materials (IFSA 2017). Figure 4 shows the global market size and market sales price of the discussed carbon morphologies.

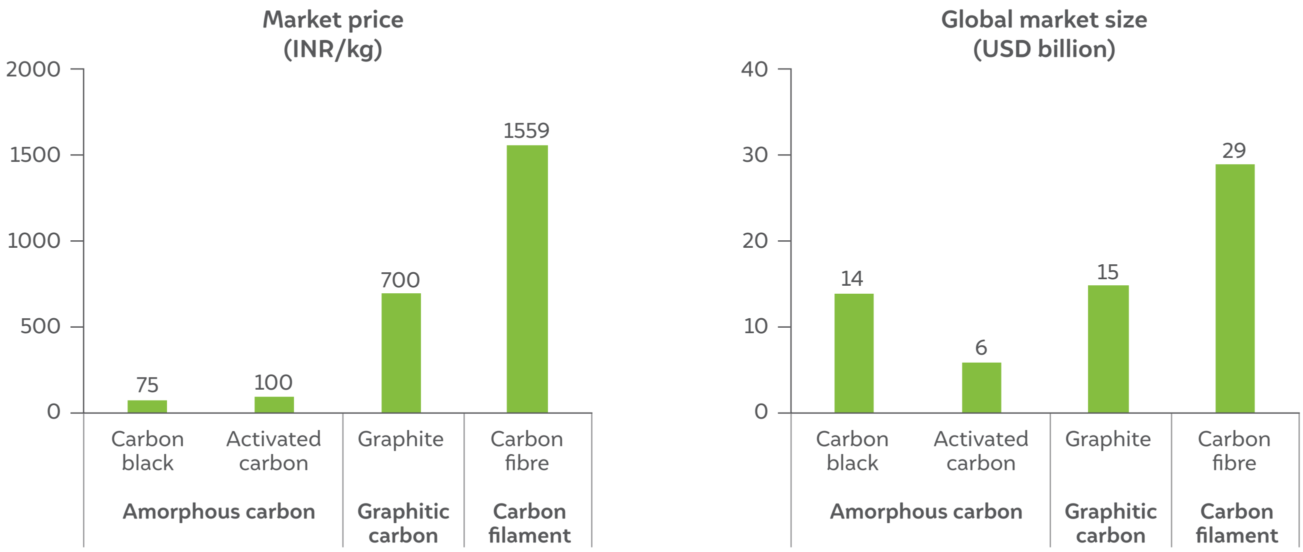
**Figure 3** **Some examples of carbon morphologies that can be obtained through pyrolysis**




*Source: Wikimedia Commons*

Note: At sufficiently high temperatures, turbostratic carbon spontaneously converts to graphite, which is known as graphitisation. It can also be converted to activated carbon (which consumes a part of the carbon) (Chung 2021; Ruz 2016)

**Figure 4** **High-value carbon filaments could be produced using pyrolysis**




*Source: BusinessWire (2021); Zhanga et al. (2020); Rao N, Simha, Rao, and Ravikumar (2018)*

Note: All the numbers are reported for the year 2020 using the growth rates given in the references

## 2.4 Advantages of natural gas pyrolysis

Natural gas pyrolysis technologies developed by current market players possess several advantages. The major ones are listed below.

- **Lower greenhouse gas emissions.** Hydrogen produced through natural gas pyrolysis (i.e., turquoise hydrogen) has up to 85 per cent lower emissions than SMR (see Table 1). The reduction in emissions is realisable, provided that the carbon by-product produced is not further combusted, as this would result in additional emissions of 11 kg $CO_2eq$/kg $H_2$. If it is combusted, the emissions would be higher than SMR with carbon sequestration (blue hydrogen) but still lower than regular SMR. However, it is important to note that if this by-product is combusted in place of another carbon-based fossil fuel in a different process, the upstream emissions associated with those fuels would be offset. If renewable methane, primarily biogas, is used as the feedstock for pyrolysis, the process can be categorised as carbon-negative, since atmospheric carbon dioxide would be converted to solid carbon.
- **Efficient capture of carbon by-product.** Based on the mass balance, sequestering 1 kg of solid carbon from pyrolysis is equivalent to sequestering 3.7 kg of gaseous carbon dioxide produced during SMR. Therefore, compared to blue hydrogen from SMR or coal gasification, turquoise hydrogen from pyrolysis is more amenable to sequestration. Commercial-scale post-process CCS technology (as would be used for blue hydrogen) has so far registered a capture rate of only 65 per cent of carbon dioxide in the exhaust gas stream (Jefferies 2021).
- **Ease of blending in natural gas pipelines.** For blending hydrogen with piped natural gas, pyrolysis plants can be installed at the few LNG terminals and injection points in the transmission pipeline grid that receive gas from onshore and offshore natural gas production sites and processing plants. Hydrogen-intensive industries and city gas stations could also consider pyrolysis plants to meet the hydrogen demand.
- **The growing market for carbon by-products.** There is a large and growing market for carbon by-products in the rubber and dye industries. If these by-products from pyrolysis are sold, the levelised cost of hydrogen (LCOH) will reduce. The process could be optimised to produce anything from low-grade carbon black, which can be sold for about 0.2 USD/kg, to Li-ion battery-grade graphitic carbon, priced as high as 20 USD/kg.
- **Easier adaptation for existing natural gas users.** Various sectors, such as the petrochemical, refinery, and fertiliser industries, which already utilise gas-based hydrogen production processes, could adopt this pathway to decrease their carbon footprint.

# 3. Natural gas pyrolysis economics in the Indian context

The success of natural gas pyrolysis depends on its cost-competitiveness vis-à-vis grey and green hydrogen. The levelised costs of turquoise hydrogen produced through natural gas pyrolysis are dependent on fluctuations in the price of natural gas feed, which is more expensive in India than in the U.S. or the EU, where pyrolysis technologies were predominantly developed. Additionally, the price of the by-product carbon will also significantly influence hydrogen production costs. The operational costs will vary due to the price of utilities and labour. Once these factors are accounted for, the price competitiveness of turquoise hydrogen can be assessed.

We analysed the production cost of hydrogen from natural gas pyrolysis by adapting from literature the process design parameters for the thermal (Keipi, Tolvanen, and Konttinen 2018), thermo-catalytic (Parkinson et al. 2017), and plasma (Kerscher et al. 2021) technology pathways.

**Table 4** Import and domestic factors

| Parameters | Thermal pyrolysis | Thermo-catalytic pyrolysis | Plasma-based pyrolysis |
|---|---|---|---|
| Country of origin | Finland | USA | Germany |
| Import factor | 1.50 | 1.80 | 1.80 |
| Domestic factor | 0.54 | 0.65 | 0.65 |

*Source: Garrett (1989)*

**We estimate the LCOH from pyrolysis to be as low as 1.6 USD/kg when the carbon by-product is sold.**

We used import–export factors to estimate equipment costs for the Indian context. Domestic factors were used for the equipment manufactured in India: heat exchangers, pumps, pressure swing adsorbers, compressors, settlers, boilers, expanders, and filters. The novel proprietary equipment costs for catalytic bed pyrolysis reactors, separation membranes, and carbon pelletisers were estimated using import factors as given in Table 4 (Garrett 1989). The country of origin mentioned for each process is based on the assumptions made in the literature sources referenced.

Table B in the Annexure shows the mass and molar composition of natural gas considered for this analysis. We obtained equipment costs from literature and scaled them using the appropriate scale factor given by *Coulson and Richardson's Chemical Engineering Design* (Sinnott 2005). We estimated the purchase costs for certain typical equipment (such as heat exchangers and pumps) using empirical relations and design plots where the purchase costs were not available in literature. We then scaled up the results to the current year using the Marshall and Swift Index. Table C in the Annexure shows the detailed calculations for different types of equipment.

We sized the plants for hydrogen production of 9,000 kg/hour (corresponding to 75,000 tonnes per annum considering operational availability of 8,400 hours per year), as given in Keipi, Tolvanen and Konttinen (2018). We considered a natural gas price of 8 USD/MMBtu (based on approximate average import prices retrieved from MoPNG [2022]). The ideal scenario from a cost perspective is to utilise natural gas at the point of import or injection into the pipeline grid. The levelised cost of hydrogen (LCOH) will increase further if the natural gas has to be moved through the pipeline network before pyrolysing. For the plasma process, which uses electricity as the energy source, we considered average grid electricity prices of 8.6 INR/kWh for industrial consumers (Central Electricity Authority 2020).

In 2019–20, India imported coking coal at 11.8 INR/kg to produce coke used in blast furnaces; this is equivalent to about 20 INR/kg of coke (considering 1.7 kg of coal per kg of coke) (Department of Commerce 2022). It also imported carbon black for the rubber industry at 79 INR/kg (Department of Commerce 2022). Based on these prices, we can assume a by-product carbon price of 0-80 INR/kg. However, the weighted average by the quantity of imports is only 20.4 INR/kg (Department of Commerce 2022). Therefore, to be conservative, we considered by-product carbon prices of 0 and 0.4 USD/kg. However, certain companies claim to produce allotropes of carbon, such as graphene, which can fetch a much higher value and consequently result in a much lower LCOH (see Section 3.2.2 for sensitivity analysis).

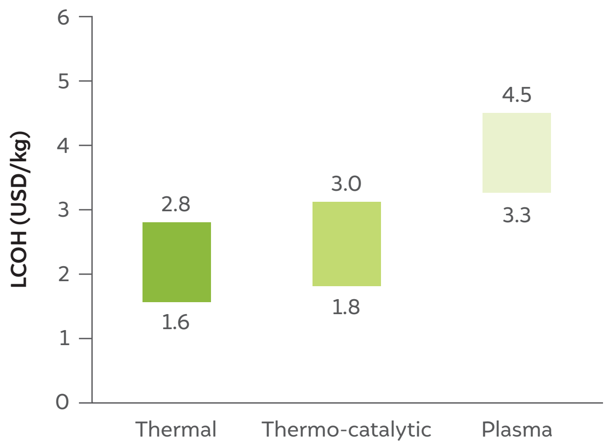
## 3.1 Findings

Figure 5 compares the LCOH of the three natural gas pyrolysis technologies when adapted to an Indian context. Based on our analysis, the LCOH of thermal pyrolysis, the cheapest process, is estimated to be around 2.8 USD/kg $H_2$, assuming that the by-product carbon is not sold. If the by-product carbon is sold for 0.4 USD/kg, the resulting cost of hydrogen drops to 1.6 USD/kg.

The thermo-catalytic process is marginally more expensive; however, as mentioned in Section 2.1, it allows better control over the quality of the carbon by-product. As plasma pyrolysis can use renewable electricity to produce heat, this process can be made emission-free. In contrast, thermal and thermo-catalytic processes rely on the combustion of natural gas to provide the process heat. The plasma pyrolysis process is more expensive and uses proprietary technology for the plasma generator, leading to varying component costs depending on the manufacturer and the source of plasma (whether it is thermal or non-thermal) (Transform Materials 2021; Monolith Materials 2021). Thermal sources include an electric arc, whereas non-thermal plasma can be produced using dielectric barriers, microwaves, or electron beams. There are methods of producing plasma with much cheaper components, such as arc-based non-thermal plasma. However, we could not cite reliable and credible sources on the costs of such components other than electron accelerators at the time of writing.

The estimates provided in Figure 5 consider the price of electron accelerators for electron beam plasma pyrolysis (Kerscher et al. 2021). Commercially available plasma generators cost 600 to 1,100 USD/kW (OSTI 2017; Chmielewski 2011). In Figure 5, we have assumed that electron accelerators of the required specifications can be domestically sourced. If imported, then the LCOH increases by 97 per cent (for 0 USD/kg sale price of by-product carbon) to 73 per cent (for 0.4 USD/kg sale price of by-product carbon).

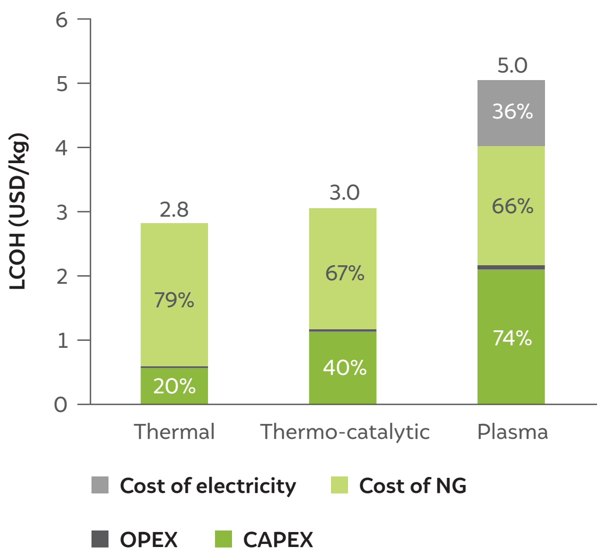
**Figure 5** **Thermal and thermo-catalytic pyrolysis are price-competitive**




*Source: Authors' analysis*

Note:
1. The price range corresponds to carbon by-product selling price of 0.40 USD/kg to 0 USD/kg
2. Natural gas price assumed to be 8 USD/MMBtu
3. The LCOH from plasma pyrolysis assumed the use of a domestically sourced electron accelerator. If imported, the LCOH increases by 4–5 USD/kg

**Figure 6** **The LCOH breakdown shows that CAPEX is a significant component for plasma pyrolysis**




*Source: Authors' analysis*

Notes:
1. The total cost above the columns does not include the offset from the sale of carbon.
2. A carbon by-product selling price of 0.4 USD/kg would reduce the hydrogen price by 1.2 USD/kg.
3. Natural gas price assumed at 8 USD/MMBtu.
4. The cost of electricity for auxiliary utilities is excluded from the plot above as it is insignificant.

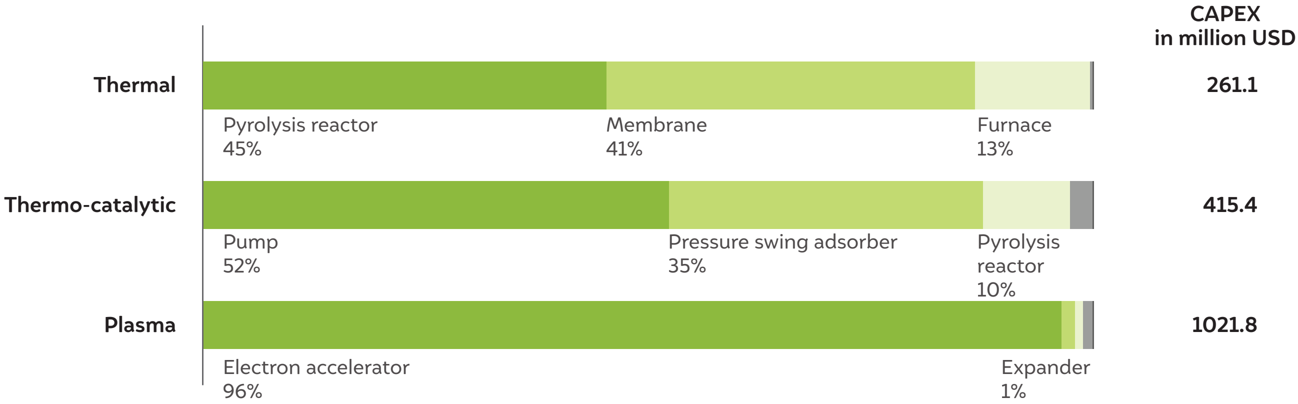
The contribution of capital expenditure (CAPEX) and operating expenditure (OPEX) (chiefly, the cost of natural gas and electricity) to the LCOH is shown in Figure 6. In this figure, the LCOH is based on a gas price of 8 USD/MMBtu. For thermal pyrolysis, the cost of the natural gas feed and fuel is the main component of the LCOH, whereas, for plasma pyrolysis, the CAPEX is the major contributor. Since the plasma process uses electricity as the energy source, the share of the electricity cost is shown separately.

Figure 7 shows the total cost for each pyrolysis technology considered, broken down by its components. The capital costs correspond to a production capacity of 9,000 kg/hour, operating for 8,200 hours/year on average. Thermal pyrolysis plants are the cheapest option, where the major cost components are the reactor vessel and the separation membrane for recycling undecomposed methane. The two major cost components for the thermo-catalytic process are the molten salt pump (for heat transfer and carbon removal) and the pressure swing adsorber (for separating hydrogen and undecomposed methane).

In the configuration considered in our analysis, plasma pyrolysis requires expensive electron accelerators to produce plasma, making up 96 per cent of the capital if procured domestically. As mentioned earlier, we assumed that the electron accelerator for plasma beam production is manufactured domestically (which currently is not the case). If the accelerator is imported, then the CAPEX will rise significantly to nearly USD 2.8 billion, raising the hydrogen price to 8.7 USD/kg (without selling the by-product carbon). Due to the prohibitive price of imported plasma technology, this option was not explored further.

Figure 8 compares the capital costs of equivalently sized hydrogen production plants based on various technologies. It can be observed that thermal and thermo-catalytic pyrolysis are significantly more capital intensive than SMR. However, from an emissions perspective, a comparison of SMR with CCS and the pyrolysis techniques is relevant, and the costs are comparable. The advantage with pyrolysis, however, is that it has a higher technology readiness level, with at least commercial plants already in place. On the other hand, CCS has not been tried out in India, and no infrastructure currently exists.

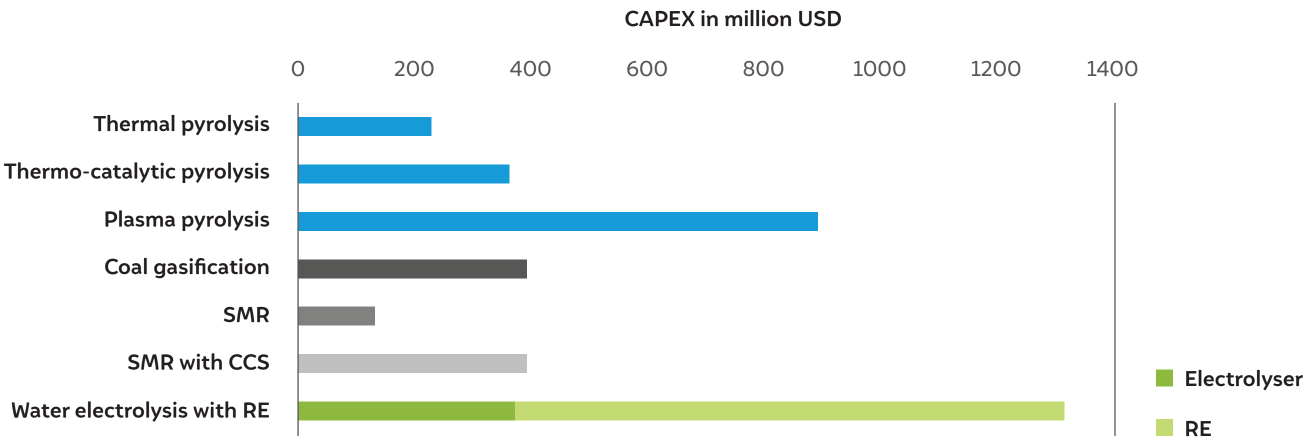
**Figure 7** The capital cost breakdown comparison shows that thermal pyrolysis is the cheapest option




*Source: Authors' analysis*

Notes: The costs correspond to a hydrogen production capacity of 9,000 kg/hour, operating for 8,200 hours/year on average.

**Figure 8** A capital cost comparison shows that pyrolysis is competitive with alternate hydrogen production pathways




*Source: Authors' analysis*

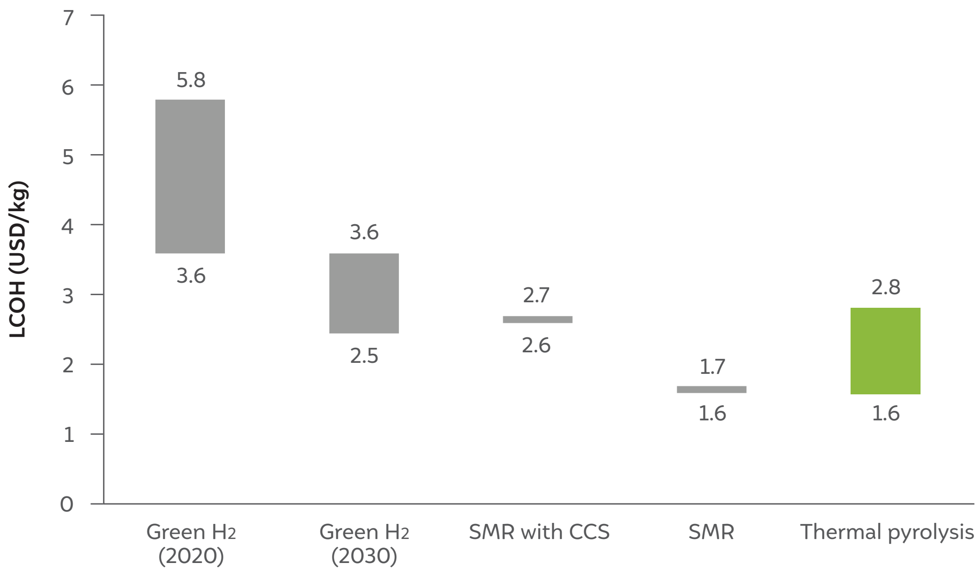
Notes:

1. The costs correspond to a hydrogen production capacity of 9,000 kg/hour, operating for 8,200 hours/year on average.
2. SMR costs adapted from (IEAGHG 2017) using factors given in Table 4.
3. The CAPEX on water electrolysis with renewable energy includes the CAPEX for the required captive renewable power plant; sourced from the authors' analysis.

Pyrolysis has much lower CAPEX requirements than a water electrolysis plant (for green hydrogen), as the latter requires significant upfront investments not just for the hydrogen production plant but also for establishing captive renewable power plants with energy storage. However, the operating costs of electrolysis plants will be much lower as there is no need for expensive feedstock such as natural gas. Further, the CAPEX requirement reduces significantly if the renewable power is wheeled-in through the power transmission grid. However, in such a scenario, the variable cost will go up considerably as it is costly to wheel power from RE generation sites to end-users due to high transmission charges.

As illustrated in Figure 9, turquoise hydrogen is cheaper than blue hydrogen (SMR with CCS), priced at 2.6–2.7 USD/kg $H_2$. It is also competitive with the estimate of the green hydrogen price for 2030 (Biswas, Yadav and Baskar 2020). Some Indian companies have announced a target of achieving 1 USD/kg $H_2$ in a decade (Press Trust of India 2021; Koundal 2021). According to our modelled estimates, such targets are relatively ambitious and may not be realistically possible without a steep decline in component costs, increase in equipment efficiencies, and resolution of power market issues over a short period of time (Yadav, Guhan, and Biswas 2021).

**Figure 9** Hydrogen from natural gas pyrolysis is cheaper than the water electrolysis route and comparable with SMR with CCS




*Source: Authors' analysis; Biswas, Yadav and Baskar (2020)*

Notes:

1. The range of green hydrogen costs depends on the choice of alkaline (cheaper) or polymer electrolyte membrane (costlier) electrolyser.
2. SMR and pyrolysis LCOH are shown for a gas price of 8 USD/MMBtu. The upper and lower bounds for SMR depend on operational characteristics and capacity utilisation. The upper and lower bounds for pyrolysis depend on the selling price of the carbon by-product.

Green hydrogen is also cost-competitive when renewable energy is coupled with hydrogen production in a captive unit. However, the current end-use sectors are not all located in renewable energy–rich regions, and the high cost of transmitting power will increase the cost of the delivered hydrogen. Further, since green hydrogen relies on renewable power systems, ensuring 24 x 7 supply requires expensive energy storage systems, which would significantly increase the average price of hydrogen. To avoid this, blending green hydrogen with a certain percentage of grey/blue/turquoise hydrogen would be necessary for consumers having continuous demand requirements (Yadav, Guhan and Biswas 2021). Here, blending turquoise hydrogen instead of grey hydrogen would allow for lower overall emissions.

## 3.2 Sensitivity analysis

We examined the impact of varying natural gas prices and differing market values of the carbon by-product on the price of hydrogen. In the base case, we considered a cost of 8 USD/MMBtu for natural gas and applied a value of either 0 or 0.4 USD/kg to the carbon by-product.

### Effect of natural gas prices

India is dependent on imports of natural gas for about 55 per cent of its demand (MoPNG 2022). Global gas prices tend to rise and fall depending on the demand–supply balance and can sometimes rise sharply due to certain issues (such as demand spikes, supply issues, etc.). Global gas prices have been elevated since the last two quarters of 2021–22. While Asian spot LNG prices saw a historic spike to about 85 USD/MMBtu due to the geopolitical crisis in Europe (S&P Global 2022), most of India's imports are secured through long-term contracts that have price ceilings. Therefore, the average import price for the last quarter of 2021–22 increased to 14.2 USD/MMBtu (Department of Commerce 2022) when the average Brent crude price hovered at around 90 USD/Bbl (Trading Economics 2022). To reflect such events, we calculated the price of turquoise hydrogen from thermal pyrolysis for natural gas prices of 10 and 14 USD/MMBtu. The results are shown in Figure 10.

Even if natural gas is procured at 14 USD/MMBtu, turquoise hydrogen will still be price competitive with green hydrogen (priced at 3.6–5.8 USD/kg, as shown in Figure 9). Note that the price of grey hydrogen would also increase corresponding to the price of natural gas; thus, the comparison between grey and turquoise hydrogen will not change significantly with the gas price.

### Effect of carbon by-product prices

The selling price of the carbon by-product from pyrolysis depends on various factors such as the quality and morphology of the carbon, existing and new markets for carbon, and the potential for this carbon to replace other materials such as coke in steel-making. Our base case price of 0.4 USD/kg corresponds to the approximate average import price of carbon black (Department of Commerce 2022).

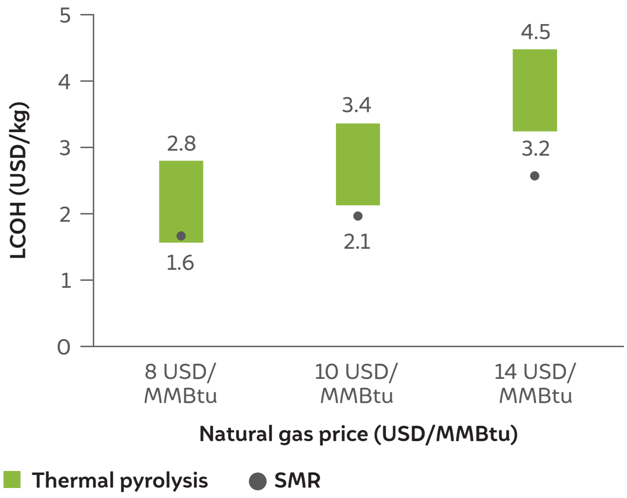
However, if carbon black from pyrolysis were to replace imported coke or coking coal (as discussed in Section 4.2), then it would have a lower value of about 0.25–0.27 USD/kg (Department of Commerce 2022). Conversely, if 10 per cent (realistically) of the carbon by-product is in the form of graphite or carbon nanotubes, a much higher value of about 1 USD/kg could be realised. Figure 11 shows the sensitivity of the turquoise hydrogen price to the price of the carbon by-product. We have considered thermo-catalytic pyrolysis as the base for this sensitivity since more advanced forms of carbon require catalysts (see Section 2.3).

Thus, if advanced forms of carbon can be produced and sold at current market prices, the effective price of turquoise hydrogen can be brought down significantly. Even if only 10 per cent of the carbon is valued at 1 USD/kg, it could reduce the hydrogen cost from 1.8 to 1.6 USD/kg (assuming the remaining carbon is sold at 0.4 USD/kg). However, if excess carbon is produced beyond the capacity of existing and new markets, the value of the carbon would reduce drastically. Careful consideration is needed to ensure that sufficient demand for carbon by-products exists to maintain competitive prices.

# 4. Natural gas pyrolysis: opportunities

Natural gas pyrolysis technology can be deployed at scale to ease the transition to a green hydrogen economy, both from the supply and demand sides. Pyrolysis plants can be set up within industrial premises to meet their hydrogen demand—for example, in refineries and petrochemical units. Integrated steel plants could deploy natural gas pyrolysis plants to blend hydrogen with natural gas for use in shaft furnaces to produce direct-reduced iron. The by-product carbon can also be internally consumed in a blast furnace, thus offsetting the need for imported coking coal.

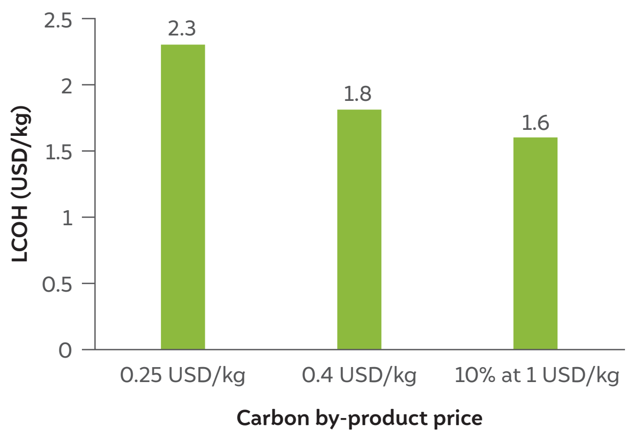
**Figure 10** High gas prices affect both SMR and thermal pyrolysis comparably




*Source: Authors' analysis using information from MoPNG (2022), Biswas, Yadav and Baskar (2020)*

Notes:
1. Grey dots indicate the approximate price of grey hydrogen from SMR for the corresponding gas prices.
2. Price range corresponds to 0.4 USD/kg (lower end) to 0 USD/kg (upper end) of carbon by-product selling price.

**Figure 11** Utilising thermo-catalytic pyrolysis could allow for a much higher value of carbon by-product




*Source: Authors' analysis using information from the Department of Commerce (2022)*

Notes:
1. Natural gas priced at 8 USD/MMBtu considered.
2. For the third case, the remaining 90% of carbon is valued at 0.4 USD/kg.

Hydrogen from pyrolysis can be blended with piped natural gas to reduce the carbon footprint of natural gas consumers. In all these cases, pyrolysis will be commercially feasible if the turquoise hydrogen production centre is located close to either the natural gas production/gas processing location or LNG import terminals. The addition of natural gas transmission tariffs and taxes will drive up the price of the delivered natural gas. This will significantly increase the cost of turquoise hydrogen production at the point of end-use (far from natural gas production/processing sites or LNG terminals). In Sections 4.1 and 4.2, we look at the potential for pyrolysis deployment in India to blend hydrogen into the natural gas grid and use cases for the carbon by-product in existing or new markets.

## 4.1 Blending turquoise hydrogen with piped natural gas

The Government of India is working on rapidly expanding the natural gas pipeline infrastructure in the country. The current gas pipeline infrastructure, with a cumulative length of 19,998 km (including 24 km of offshore pipelines) and a capacity of nearly 350 million metric standard cubic metres per day (MMSCMD), supports many gas-intensive sectors (MoPNG 2022; MoPNG 2021b). This is expected to expand to 34,900 km and 815 MMSCMD by 2030 (MoPNG 2021b). The extensive pipeline network would enable greater decarbonisation opportunities by blending hydrogen with natural gas and eventually supporting the switch to green hydrogen where needed.

Natural gas is injected into the pipeline network at limited points – at LNG import terminals and domestic production sites. About 55 per cent of the gas is imported in the form of LNG, which enters the national gas value chain from six LNG terminals (MoPNG 2022). Setting up pyrolysis plants adjacent to the regasification units at these terminals would allow the blending of a significant amount of hydrogen with natural gas. In the case of domestic production sites, 30 per cent of the total natural gas supply comes from the onshore gas processing unit in Uran (MoPNG 2022). Hence, operating seven pyrolysis plants (six LNG terminals and Uran) at the above locations would cover almost 70 per cent of the total natural gas supply.

Assuming an annual natural gas demand of 55 billion cubic metres (bcm), and a 15 per cent blend of hydrogen by volume, a pyrolysis plant with an average capacity of 95 ktpa (around 11,300 kg $H_2$/hour) of hydrogen would be required at each of the seven locations. To produce this quantity of hydrogen from pyrolysis, an additional natural gas volume of around 5.3 bcm/year would be required, costing nearly USD 1.7 billion at a gas price of 8 USD/MMBtu. A plant of this size utilising the thermal process would require an initial investment of approximately USD 318 million. Figure 22 represents the possible injection points where a pyrolysis plant could be located for introducing hydrogen into the gas network.

With a 15 per cent volumetric blend of hydrogen, approximately 5.8 million tonnes of $CO_2$ emissions can be abated annually, considering the present demand for natural gas.

The use of natural gas pyrolysis will quite likely increase LNG imports as domestic natural gas production is not expected to compensate for imports. However, natural gas pyrolysis is meant to be a temporary arrangement for the next decade or so until green hydrogen costs adjust downward and scale is achieved. Post that, green hydrogen, being a domestic source of energy at cost parity with turquoise hydrogen, will automatically displace it without any barriers, i.e., there will be no commercial motivation to continue with turquoise hydrogen. The pyrolysis pathway may persist if the carbon by-products provide valuable materials like graphite. However, even in this case, the scale will reduce as the focus will again be on carbon and not the large volumes of hydrogen that are required.

## 4.2 Market opportunities for by-product carbon

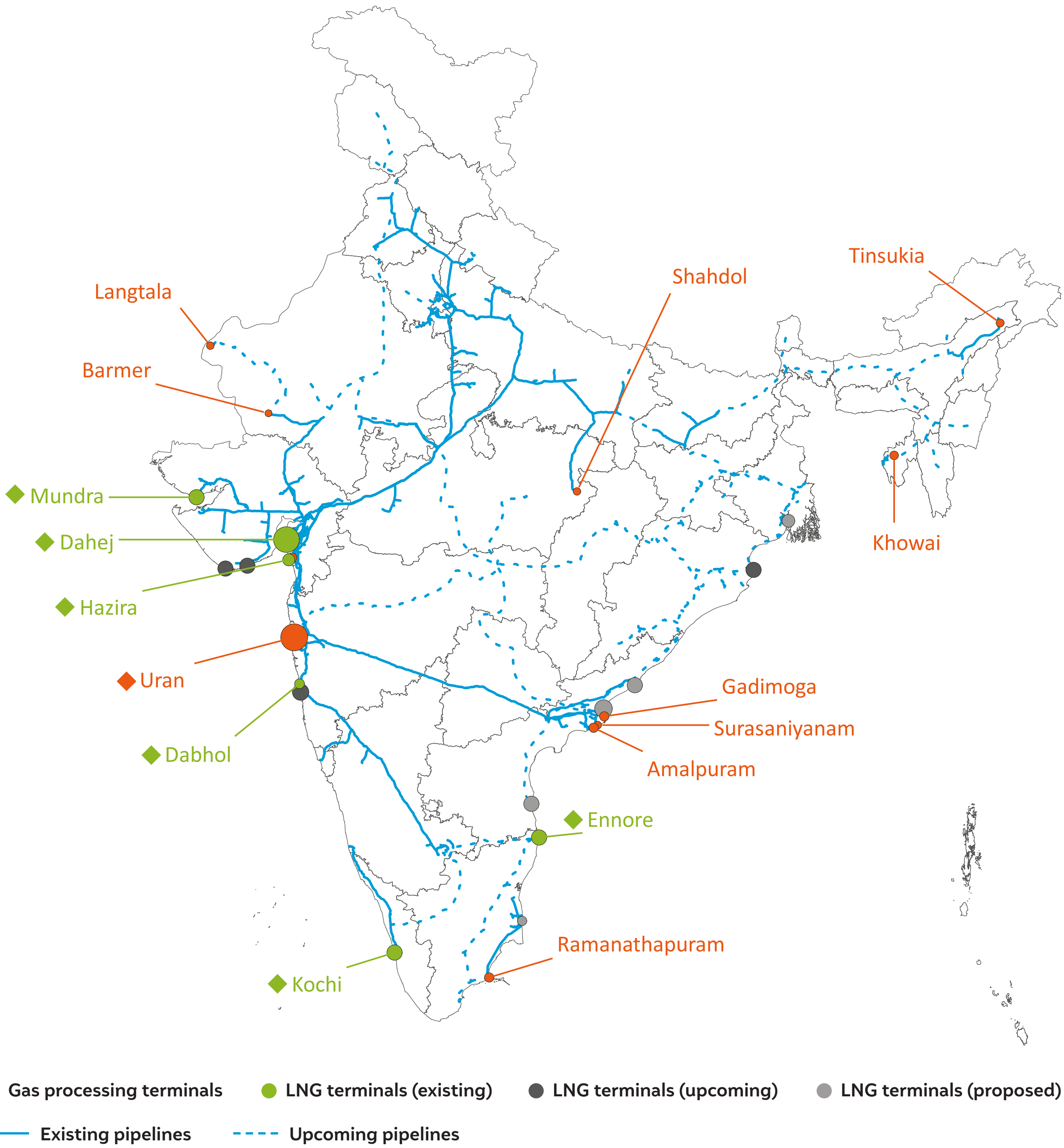
As inferred from Figure 9, turquoise hydrogen will still be competitive even if the carbon by-product is not sold. The cost of disposing of this carbon in a landfill is as low as 0.02 USD/kg (Department of Economic Affairs 2009) (2009 costs inflated to 2020). However, in the initial stages of its introduction to the Indian market, it is essential to understand the market for the carbon by-product and strategies to expand it. We have considered opportunities to sell the carbon to improve the competitiveness of turquoise hydrogen with grey hydrogen.

### Carbon black

- Carbon black has the largest market share among all the allotropes because it is widely used in tyres, paints, dyes, coatings, cosmetics, the paper industry, and in refractory products (PentaCarbon 2021). It is popularly produced via two pathways – the furnace black and thermal black processes (ICBA 2021).

> **Natural gas pyrolysis technology can be deployed at scale to ease the transition to a green hydrogen economy.**

**Figure 12** **Possible injection point locations for blending hydrogen with piped natural gas**




*Source: Authors' analysis; PNGRB (2021)*

Note: Diamonds next to the name indicate the proposed locations for setting up pyrolysis plants.

The furnace black process uses heavy aromatic oils as feedstock, whereas the thermal black process primarily uses natural gas. The demand for carbon black in India stood at nearly 1.3 Mt in 2018 according to the Rubber Industries Association (Kumar 2018).

In the same year, the domestic availability was about 1 Mt, making India heavily dependent on imports, especially from cheap carbon black exporters such as China. If pyrolysis capacity is scaled up to meet 15 per cent pipeline blending of hydrogen with natural gas, imports worth around USD 200 million of carbon can be substituted with domestic sources (Department of Commerce 2022).

- The prospect of carbon black replacing coke in blast furnaces for steel manufacturing needs to be explored. India imported more than 50 million tonnes of coking coal in 2019–20, worth nearly USD 8.7 billion (Ministry of Coal 2021; Department of Commerce 2022). Around 1.7 units of coking coal approximately correspond to 1 unit of coke. If the 2 Mtpa of carbon by-product from the seven pyrolysis plants (of 95 ktpa $H_2$ capacity each) were to substitute coke, 3.4 Mtpa of coking coal imports (worth USD 567 million) could be avoided. This use case needs to be validated, as there may be a need to pre-process the carbon black to meet proximate composition and hardness requirements before it can be used in a blast furnace. For integrated plants with blast furnaces, capacity expansion can occur through hydrogen-based direct reduction. Here, hydrogen can be obtained through natural gas pyrolysis (Bhaskar, Assadi and Nikpey 2021), and the carbon black can potentially replace coke in existing blast furnaces.

- Carbon black has potential applications in the manufacture of sodium-ion batteries (Xiao et al. 2017), which are being developed as alternatives to lithium-ion and lithium phosphate batteries.

- The application of carbon black as a filler and pigment in cement has also been studied (Masadeh 2015; Priya 2016; Fayaz, Zakir, and Malik 2018). Up to 5–8 per cent can be blended with cement to improve its tensile strength. This could create a carbon sink of about 27.5 Mt, assuming an annual cement production of over 500 Mt in India. Moreover, carbon black has also been validated as a replacement for coal as a source of energy in the cement industry (Sarawan and Wongwuttanasatian 2013).

## Graphite

- With electric vehicles gaining popularity, the demand for graphite for use in lithium-ion batteries is bound to increase exponentially. We expect 14.8 million electric vehicles to be on roads in India by 2030, which would correspond to 158 GWh of battery capacity (CEEW-CEF 2021). Typically, 1.2 kilogrammes of graphite is required per kWh of battery capacity, totalling to a total graphite consumption of 190,000 tonnes (InvestorIntel 2017). Such graphite used in energy storage applications must have a purity of at least 99.99 per cent.

  At least one of the major developers of natural gas pyrolysis technology has developed a proprietary reactor to produce battery-grade graphite (Hazer Group 2018). Generally, post-processing may be required to achieve the desired purity. Standard purification techniques for battery-grade graphite can be performed at a cost of around 3–5 USD/kg (Focus Graphite 2021). Battery-grade natural graphite sells for 2.5–3 USD/kg making synthetically manufactured graphite from natural gas pyrolysis highly cost competitive (Jaraa, Betemariam, Woldetinsae, and Kim 2019). Such synthetically manufactured graphite from natural gas pyrolysis would also help offset the ecological footprint of mining for flake graphite in India.

**If the 2 Mtpa of carbon by-product from the 7 pyrolysis plants (of 95 ktpa $H_2$ capacity each) were to substitute coke, 3.4 Mtpa of coking coal imports (worth USD 567 million) could be avoided.**

## Other

- In 2019, India was the third-largest exporter of activated carbon in terms of volume, with more than 20,000 tonnes exported (Trend Economy 2019; IndexBox 2020; Department of Commerce 2022). Traditionally, activated carbon is produced using coconut shells. However, there are demonstrated technologies to convert carbon black to activated carbon at a low cost (USA Patent US6337302B1 1998). Exported activated carbon is priced at approximately 1.4 USD/kg, thus creating an enormous potential for increased profit margins (Department of Commerce 2022).

- The possibility of using the carbon by-product for producing electrodes utilised in Hall-Héroult's process could also be explored (American Chemical Society 1997). In the Hall-Héroult process, a carbon electrode is consumed for producing aluminium. Typically, one kilogramme of carbon anode would produce three kilogrammes of aluminium. In 2020, India manufactured 3.6 Mt of refined aluminium, corresponding to a net carbon consumption of 1.2 Mt. Hence, this industry could provide a sizeable sink for the carbon by-product from pyrolysis. The use of the by-product carbon would offset the life cycle emissions of producing the electrode through other pathways.

- Acetylene is used in oxy-acetylene flames and as a feed for manufacturing industrial chemicals such as polyvinyl chloride, acrylonitrile, vinyl acetate, and vinyl ether. In 2020, India's vinyl chloride monomer production stood at 1.6 Mt (Research and Markets 2020). A steady supply to vinyl chloride monomer plants could be guaranteed with natural gas pyrolysis plants running on microwave-generated plasma, which produces acetylene alongside hydrogen.

## 5. Natural gas pyrolysis: challenges

Though the technology seems quite promising, there are a few challenges associated with pyrolysis that need to be addressed.

- **Early stages of commercialisation**. Though the principal technology of pyrolysis was discovered in the 1980s, it was not optimised for hydrogen production until recently (Monolith Materials 2021). Hence, only a small number of demonstration projects with hydrogen as the primary output have been commissioned. Monolith Materials is currently the market leader with two commercial plants in the United States. Transform Materials has validated its technology at a pilot scale and is in the initial stage of constructing a full-scale commercial plant. The remaining companies are yet to validate their process on a pilot scale. For pyrolysis to act as a bridge until green hydrogen is price competitive, pyrolysis plants must soon be readied for commercial-scale deployment.

- **By-product end-use capacity**. For a kilogram of methane feed, about 0.75 kilogram of carbon is formed while the rest is hydrogen. If the total natural gas demand were blended with 15 per cent hydrogen by volume, the annual carbon production would be 2.3 Mt. This amounts to over 2.3 times the annual demand for carbon black, which has the highest market share among all the carbon allotropes because of the sizeable tyre industry in India. Therefore, the expansion of pyrolysis capacity for hydrogen blending should take into account existing and future markets for carbon black and other forms of carbon that can be produced through pyrolysis. It is also important to understand the additional expenditure needed for its disposal and the potential environmental issues if no end-uses are found.

- **Price of natural gas**. India has limited gas production; imported LNG contributes to roughly 55 per cent of its supplies. Imported LNG is expensive and its price is pegged to oil markets. However, our analysis shows that even at the average crude oil price of 90 USD/Bbl in the fourth quarter of 2021–22

> **Expansion of pyrolysis capacity for hydrogen blending should take into account existing and future markets for carbon black and other forms of carbon.**

(Trading Economics 2022), the landed price of LNG in India was approximately 14.2 USD/MMBtu (spot + long-term contract purchases) (Department of Commerce 2022), which will yield turquoise LCOH competitive with green hydrogen today. Besides, the cost of fossil fuels is cyclical; gas prices over the last decade have averaged out to 8.3 USD/MMBtu (MoPNG 2022, MoPNG 2016). Hence, long-term LNG contracts should largely allay the issue of fluctuations in natural gas prices.

- **Natural gas lock-in concerns**. As the world moves away from fossil fuels to address climate change, a key concern with natural gas pyrolysis is that it will lock in additional volumes of natural gas in the longer term. This, however, may not be a concern in the Indian context for two reasons. First, green hydrogen is expected to achieve cost parity with turquoise hydrogen in the next 10–15 years in India. Thus, the commercials will automatically push out turquoise hydrogen from the market. Second, pyrolysis in India will have to rely on imported LNG, and there will be minimal resistance to phasing out this import over time.

- **Methane emissions from natural gas supply chains**. Over the last decade, there has been a heightened awareness of natural gas/methane emissions from the natural gas supply chain. Methane is a 29.8-times more potent greenhouse gas than carbon dioxide over a 100-year time period (ERCE 2021). However, there are tangible and cost-effective options to mitigate methane emissions (ICF International 2016). International programmes such as the Global Methane Initiative, Oil and Gas Methane Partnership and Global Gas Flaring Reduction Partnership are targeting a reduction in methane emissions in the oil and gas industry. Several countries have signed the Global Methane Pledge to reduce methane emissions from all sources by at least 30 per cent by 2030 from 2020 levels. Finally, several oil and gas companies and LNG suppliers are planning to introduce certification for low-methane natural gas supplies. All these efforts are expected to significantly reduce methane emissions from the oil and gas supply chain.

# 6. Recommendations

It is important to highlight that hydrogen from pyrolysis must be considered a short- to medium-term solution to be used only until green hydrogen infrastructure is fully established. However, there could be significant value in exploring pyrolysis for both creating an ecosystem for green hydrogen and for substituting carbon in other industries. Below are some key recommendations to leverage natural gas pyrolysis as an interim pathway to a hydrogen economy.

- **Scale up the hydrogen economy through pyrolysis**: The government should lay emphasis on scaling up the hydrogen economy by including turquoise hydrogen in any hydrogen purchase obligations. This can apply to refineries, fertiliser plants, and natural gas pipeline injection points that are located close to LNG terminals, gas production sites, or processing plants. This will create a market for green hydrogen consumption. The hydrogen ecosystem, and especially end-users, will take time to adapt to utilising hydrogen as a fuel. This will slow the scaling up of green hydrogen production and keep its production costs prohibitively high. Turquoise hydrogen can help address both these challenges as scaling up its production can happen relatively quickly and cheaply. The upfront capital requirements are significantly lower for natural gas pyrolysis plants compared to green hydrogen production facilities.

  A key concern is whether natural gas pyrolysis will get locked-in in the long term, hindering the shift to green hydrogen. However, in the Indian context, this may not pose a challenge as there will be no commercial sense in continuing with turquoise hydrogen made from imported natural gas over cost-competitive domestically produced green hydrogen. In any case, the government can mandate sunset clauses for accepting turquoise hydrogen as part of purchase obligations to ease it out of the system. It also has other levers, such as differential taxation, to prioritise green hydrogen in a decade or so. Further, after scaling up green hydrogen production, turquoise hydrogen could still be used to supplement hydrogen output during periods of low renewable electricity output (as mentioned in section 3.1).

- **Pilot natural gas pyrolysis**: The different pyrolysis pathways for producing hydrogen and carbon should be piloted at a suitable location. Apart from testing the technology for use in India, the study should have a twofold objective – first, to test infrastructure and end-use equipment with turquoise hydrogen, and second, to establish the chemistry and end-use market for the by-product carbon. A plant can be set up in an industrial area such as Hazira, which is near a natural gas source (such as an LNG terminal), hydrogen consumers (such as refineries), and potential carbon consumers (such as steel plants). Such a study could be commissioned as a public–private partnership with an interested corporation and a technology provider.

  This report finds that thermal pyrolysis is the cheapest option. However, we note that thermo-catalytic and plasma pyrolysis are still in the early stages of development. We expect the cost to reduce as the technology matures and scales. Further, the higher cost of thermo-catalytic pyrolysis may be easily offset through the sale of better morphologies of carbon, thus reducing the LCOH (see Figure 4 and Section 3.2.2). Hence, piloting may be considered for all types of pyrolysis to determine the most promising option for India.

> **There could be significant value in exploring pyrolysis for both creating an ecosystem for green hydrogen and for substituting carbon in other industries.**

- **Blend turquoise hydrogen with natural gas**: Since pyrolysis uses natural gas, it is easy to integrate it into a pipeline network as compared to green hydrogen, which may not be produced near the pipeline and is hence more expensive to transport. Therefore, pyrolysis provides an opportunity to incrementally and cost-effectively decarbonise the natural gas demand base. Deploying pyrolysis plants (of 95 ktpa $H_2$ capacity each) near seven existing pipeline injection points (LNG terminals and gas processing sites) could offer an opportunity to seamlessly blend 15 per cent of hydrogen by volume with natural gas. This would involve a total capital investment of USD 318 million for a plant at each of the seven major aforementioned natural gas injection points.

- **Convert existing plants to use natural gas**: Currently, several thermal pyrolysis plants in India use residual fuel oils as feed to produce carbon black. The possibility of substituting naptha with natural gas in existing carbon black plants can be explored.

The hydrogen produced could potentially be supplied to consumers nearby via pipelines. This pathway is being researched in the United States in partnership with Birla Carbon (National Energy Technology Laboratory 2021).

- **Leverage market opportunities for by-product carbon**: As mentioned in Section 3.2, the final price of hydrogen is highly sensitive to the selling price of the carbon by-product. Hence, relevant entities must look at creating new markets for the carbon by-product and expanding existing markets. Utilising carbon black from pyrolysis to satisfy the domestic carbon black demand from the rubber, dyes, and pigments industries could avoid imports of carbon black worth around USD 200 million. India imported more than 50 Mt of coking coal for use in the steel industry. If the steel industry uses the by-product carbon from the seven pyrolysis plants, the country could offset 3.4 Mtpa of coking coal imports (worth USD 567 million). The cost and emissions of coke-making are also negated. The production of carbon electrodes for aluminium manufacturing using carbon black as a feed can also be explored.

  Pathways for producing activated carbon using carbon black need to be piloted. These developments would enable the integrated use of carbon by-products, where the emissions from traditional carbon extraction, processing, and utilisation would be offset.

Overall, natural gas pyrolysis can be an effective means of building demand and infrastructure for hydrogen in India, while indirectly offsetting emissions in carbon supply chains in other industries. With deployment at scale, pyrolysis has the potential to produce high-value carbon by-products for both current and future applications. This enables the production of hydrogen at highly competitive prices with much lower emissions than incumbent technologies.

> **Natural gas pyrolysis can enable the production of cost-competitive hydrogen with high-value carbon by-products.**

# Annexures

Kværner, a Norwegian company, was the first to patent the natural gas pyrolysis technology to produce carbon black, primarily for the tyre industry, in the 1980s (Bellona Foundation 2002). By 2005, the plant had shut down as it had turned unprofitable and due to carbon black quality control issues (Gautier 2017). Monolith Materials purchased and developed this technology to become the current market leader in natural gas pyrolysis with a commercial-scale unit each in California and Nebraska (Monolith Materials 2021). However, Monolith Materials' technology uses different reaction kinetics to favour the production of carbon black. The prospect of producing hydrogen as the main output is being explored by several multinational companies, small and medium enterprises, and research organisations. Leading organisations in this field are listed in Table 3, with brief process descriptions and their respective technology readiness levels (TRL). An overview of all the technologies under development has been tabulated and can be found in Table A1 in the Annexure.

**Table A1 Natural gas pyrolysis market players**

| Name | Process | Description | Feed | By-product | TRL | Source |
|---|---|---|---|---|---|---|
| BASF, Germany | Thermal | Moving carbon bed | Natural gas, biomethane, or fuel gas | Carbon black | TRL 6 – Pilot plant under construction, full-scale by 2030 | Bode and Flick (2021); BASF (2022) |
| GAZPROM, Russia | Plasma | Microwave, closed plasma chemical flow reactor | Natural gas | Nanoscale carbon | Lab-scale. Full-scale plant in 2025–2030 in Germany with GAZPROM pipeline gas from Russia | Schneider et al. (2020); AK&M (2022) |
| TNO, Netherlands | EMBER Process - Thermal | Molten metal bubble column reactor with molten salts used for carbon separation | Natural gas, fuel gas | Carbon black | Lab-scale, full-scale by 2030–2035 | TNO (2021) |
| Monolith Materials, USA | Plasma | Feed is superheated using electricity (hot thermal plasma using a coaxial graphite electrode) | Natural gas | Carbon black (primary product) | TRL 7 – 1st demonstration plant in 2015 in California. Commercial plant in Nebraska in Q1, 2021 | Monolith Materials (2021) |
| Transform Materials, USA | Plasma | Microwave-generated plasma to split the feed molecules without combustion | Natural gas, coalbed methane, biogas, light hydrocarbons | Acetylene (primary product) | TRL 6 – Successful pilot-scale testing in May 2021 in Riviera Beach, Florida | Transform Materials (2021) |
| HiiROC, UK | Plasma | Thermal plasma electrolysis. Comparable costs with SMR. Modular system using 50 kW plasma torches | Natural gas | Char | Lab-scale. Pilot for injecting turquoise H2 in a gas power plant by Q3 2023 | HiiROC (2021); Centrica (2022) |

| Name | Process | Description | Feed | By-product | TRL | Source |
|---|---|---|---|---|---|---|
|  **Hazer Group, Australia** | Thermo-catalytic | An iron ore catalyst is used in a fluidised bed reactor with liquid natural gas, where carbon gets accumulated on the catalyst. Hazer's proprietary equipment provides high flexibility in hydrogen production and graphite purity | Natural gas and similar feedstock | Graphite | TRL 5 – Commercial demonstration pilot planned for 2023 | Hazer Group (2022); Hazer Group (2018) |
|  **EH Group, Switzerland** | Thermo-catalytic | Hydrogen stripping using microwaves to activate the iron catalytic bed at temperatures from 350°C to 600°C | All forms of methane and higher hydrocarbons (methane gives 99.8% conversion to hydrogen and decreases with decreasing H:C ratio) | Full spectrum of carbon allotropes (carbon black, graphite, needle coke, carbon nanotubes – highest fraction) | Lab-scale, expansion paused due to COVID-19 | EH Group (2020) |
|  **Hycamite, Finland** | Thermo-catalytic | FBR uses a proprietary catalyst at 500–800°C and 1 atm. Hydrogen is purified to >95% by PSA and unreacted feed is recirculated | Natural gas, biogas | The process can be optimised for the required allotrope of carbon | TRL 4 – Pilot plant under construction | Hycamite (2021); Hycamite (2022) |
|  **C-Zero, USA** | Thermo-catalytic | High-temperature multi-phase pyrolysis reactor using a proprietary catalyst | Natural gas and similar feedstock | Dense solid carbon | TRL 4 – Lab-scale, pilot-plant expected in Q1 2023 | Atlanta Council (2021); Arpa (2020); C-Zero (2021); BusinessWire (2022b) |

**Table A2** **Natural gas composition considered for technoeconomic calculations**

| Component | Mol % | No. Of H atoms | Mol. wt. (g/mol) | Grams of component/100 g NG | Weight % |
|---|---|---|---|---|---|
| **Nitrogen** | 0.40% | 0 | 14 | 0.06 | 0.31% |
| **Methane** | 90.10% | 4 | 16 | 14.42 | 80.12% |
| **Ethane** | 6.20% | 6 | 30 | 1.86 | 10.34% |
| **Propane** | 2.30% | 8 | 44 | 1.01 | 5.62% |
| **Butane and higher** | 1.00% | 11 | 65 | 0.65 | 3.61% |
| **Total** | **100.00%** | | | **17.99** | **100.00%** |

*Source: International Gas Union (2012)*

**Table A3** PCE estimation approach

| Equipment | Estimation technique | Sizing parameter | Scaling factor | Pathway | Location factor | Escalation factor |
|---|---|---|---|---|---|---|
| **Furnace** | Literature: Keipi, Tolvanen, and Konttinen (2018) | Power rating | 0.77 | Thermal | Domestic | 4.1 |
| **Carbon pelletiser** | Literature: Keipi, Tolvanen, and Konttinen (2018) | Carbon flow rate | 0.60 | Thermal, plasma | Domestic | 3.8 |
| **Carbon pelletiser*** | Literature: Keipi, Tolvanen, and Konttinen (2018), Parkinson et al. (2018) | Carbon flow rate | 0.60 | Thermo-catalytic | Import | 10 |
| **Thermal pyrolysis reactor** | Literature: Keipi, Tolvanen, and Konttinen (2018), Sinnott (2005) | Feed flow rate | 0.56 | Thermal | Domestic | 4.1 |
| **Preheater** | Design plots and empirical equation from Sinnott (2005) | Heat transfer area | 1 | Thermo-catalytic, plasma | Domestic | 6, 2.14 |
| **Expander** | Design plots and empirical equation from Sinnott (2005) | Power rating | 0.80 | Plasma | Domestic | 2.14 |
| **Plasma pyrolysis reactor** | Design plots and empirical equation from Sinnott (2005) | Volumetric flow rate | 1 | Plasma | Domestic | 2.14 |
| **Separation membrane** | Literature: Keipi, Tolvanen, and Konttinen (2018) | Mass flow rate | 0.70 | Thermal | Import | 4.8 |
| **Filter** | Sinnott (2005) | Volumetric flow rate | 1 | Plasma | Domestic | 2.14 |
| **Compressor** | Design plots and empirical equation from Sinnott (2005) | Power rating | 0.60 | Thermo-catalytic, Plasma | Domestic | 6 |
| **Electron accelerator** | Literature: Kerscher et al. (2021) | Power rating | 1 | Plasma | Imported & domestic** | 2.14 |
| **Pump** | Design plots and empirical equation from Sinnott (2005) | Power rating | 0.79 | Thermo-catalytic | Domestic | 10 |
| **Thermo-catalytic pyrolysis reactor** | Literature: Parkinson et al. (2018) | Flow rate | 1 | Thermo-catalytic | Imported | 10 |
| **Pressure swing adsorber** | Literature: Keipi, Tolvanen, and Konttinen (2018) | Volumetric flow rate | 0.60 | Thermo-catalytic | Domestic | 6 |
| **Settler** | Design plots and empirical equations from Sinnott (2005), Parkinson et al. (2018) | Volume | 0.60 | Thermo-catalytic | Domestic | 10 |
| **Waste heat boiler** | Design plots and empirical equations from Sinnott (2005), Parkinson et al. (2018) | Power rating | 0.60 | Thermo-catalytic | Domestic | 6 |

*Source: Authors' analysis*

NOTES:
*Proprietary pelletiser equipment required for thermo-catalytic pyrolysis
**Levelised costs were estimated for both – domestic and imported electron accelerators for the plasma beam pyrolysis pathway

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# Acronyms

| | |
|---|---|
| Mt | million tonnes |
| kt | kilo tonnes |
| Mtpa | million tonnes per annum |
| Ktpa | kilo tonnes per annum |
| LNG | liquefied natural gas |
| $CO_2eq$ | carbon dioxide equivalent |
| LPG | liquefied petroleum gas |
| SMR | steam methane reformation |
| NGHM | *National Green Hydrogen Mission* |
| MMBtu | million metric British thermal units |
| MMSCMD | million metric standard cubic metres per day |
| MoPNG | Ministry of Petroleum & Natural Gas |
| LCOH | levelised cost of hydrogen |
| TRL | technology readiness level |
| CAPEX | capital expenditure |
| OPEX | operating expenditure |

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*"Turquoise hydrogen can be a credible short to medium term solution for accelerating green hydrogen ecosystem development in India."*

*"Natural gas pyrolysis should be evaluated as a strategic option to provide both cheap hydrogen and carbon morphologies with new age applications."*

*"Natural gas pyrolysis produces 85 per cent lower emissions than SMR for similar or lower prices of hydrogen."*

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