MARKET ANALYSIS: UPCYCLING NATURAL GAS INTO SOLID CARBON PRODUCTS

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ACRONYMS AND ABBREVIATIONS

3D	Three dimensional
APAC	Asia Pacific
ARPA-E	Advanced Research Projects Agency–Energy
BCF	Billion cubic feet
BM^3	Billion cubic meters
CAFE	Corporate Average Fuel Efficiency
CAGR	Combined Annual Growth Rate
CCS	Carbon capture and storage
CH$_4$	Methane
cm	Centimeter
CNT	Carbon nanotube
CO$_2$	Carbon dioxide
CO$_2$e	Carbon dioxide equivalent
DOE	Department of Energy
EDF	Environmental Defense Fund
EIA	Energy Information Administration
EPA	Environmental Protection Agency
FCEV	Fuel cell electric vehicles
GGFR	Global Gas Flaring Reduction
GHG	Greenhouse gas
GJ	Gigajoule
H$_2$	Hydrogen
K	Thousand
kg	Kilogram
LADWP	Los Angeles Department of Water and Power
10^{-6}m	Micron
M	Thousand
m^3	Cubic meters
Mcf	Thousand cubic feet
MCFD	Thousand cubic feet per day
MM	Million
MMT	Million metric tons
mol%	Mole percent
MW	Megawatt electric
MWCNT	Multi-walled carbon nanotube
N/A	Not applicable/available
N$_2$	Nitrogen
NDIC	North Dakota Industrial Commission
NETL	National Energy Technology Laboratory
NOAA	National Oceanic and Atmospheric Administration
Pa	Pascal
PAN	Polyacrylonitrile
PARC	Palo Alto Research Center
PNNL	Pacific Northwest National Laboratory
psi	Pounds per square inch
SMR	Steam methane reforming
SPGMI	S&P Global Market Intelligence
SWCNT	Single-walled carbon nanotube
TCF	Trillion cubic feet
TRRC	Texas Railroad Commission
U.S.	United States
USD	United States dollar
WVU	West Virginia University
°C	Degrees Celsius
°F	Degrees Fahrenheit

EXECUTIVE SUMMARY

The purpose of this report is to execute a market analysis to determine the potential market opportunities for natural gas-derived high-value carbon products and their associated applications. Currently, associated gas is released through the process of either venting or flaring. Vented or flared natural gas is presently lost to the atmosphere, despite the fact that it represents a significant resource of both carbon and hydrogen—two products that could have significant value. Transforming some of this underutilized supply into high-cost products could contribute to realizing the full value of United States (U.S.) natural gas resources. The products analyzed in this report are carbon fiber, carbon nanotubes, synthetic graphite, and carbon black. The report also touches on the market opportunities for hydrogen, a by-product of the pyrolysis process.

To perform this analysis, market data was collected from a combination of public information and third-party market reports. A technology overview provides an understanding of the processes necessary to extract carbon from the natural gas, and transform it into a usable feedstock material. The processes considered are methane pyrolysis, catalytic thermal pyrolysis, non-thermal plasma processes, and molten metal technology. These processes are at varying levels of technology development, and each has unique energy and cost considerations.

The carbon-based products discussed in this report are high-value, high-margin products, which have applications in a diverse range of industries. They represent important elements of global technology supply chains, and reducing the cost by producing them from natural gas feedstocks could present U.S. manufacturers with a competitive advantage. The discussion of each carbon-based product covers a general market overview, manufacturing process, a high-level summary of major players in the market, and potential barriers to entry and growth.

This analysis also includes a study of the potential impacts that producing these products from natural gas could have on U.S. jobs, as well as an environmental impact of mitigating the release of natural gas to the atmosphere. The estimate of number of jobs is done using a manufacturing multiplier that is established annually by the Economic Policy Institute, using data from the U.S. Bureau of Labor Statistics. Environmental impact through mitigating emissions is derived from dry-gas production volumes reported in the *Annual Energy Outlook 2021,* and proportion of dry-gas that comes from oil wells (associated gas) in 2019 reported in the Energy Information Administration's (EIA) annual *Natural Gas Report.* Based on these derivations, there is a potential to avoid 17.14–39.86 MMT carbon dioxide (CO_2) in 2050 by upcycling all flared natural gas into products.[a]

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[a] Please refer to Appendix A: Environmental Impact Calculations for calculations.

1 BACKGROUND

This section briefly describes the activities of flaring and venting of natural gas in the United States (U.S.); the information presented here relies heavily on the Department of Energy's (DOE) 2019 Flaring and Venting report. [1] Greenhouse gas (GHG) emissions data from Environmental Protection Agency (EPA) follows, with a comment on contemporary regulatory and other actions to disincentivize flaring. Stoichiometric conversions expressing potential volumes of carbon and hydrogen products from vented/flared gas is also presented.

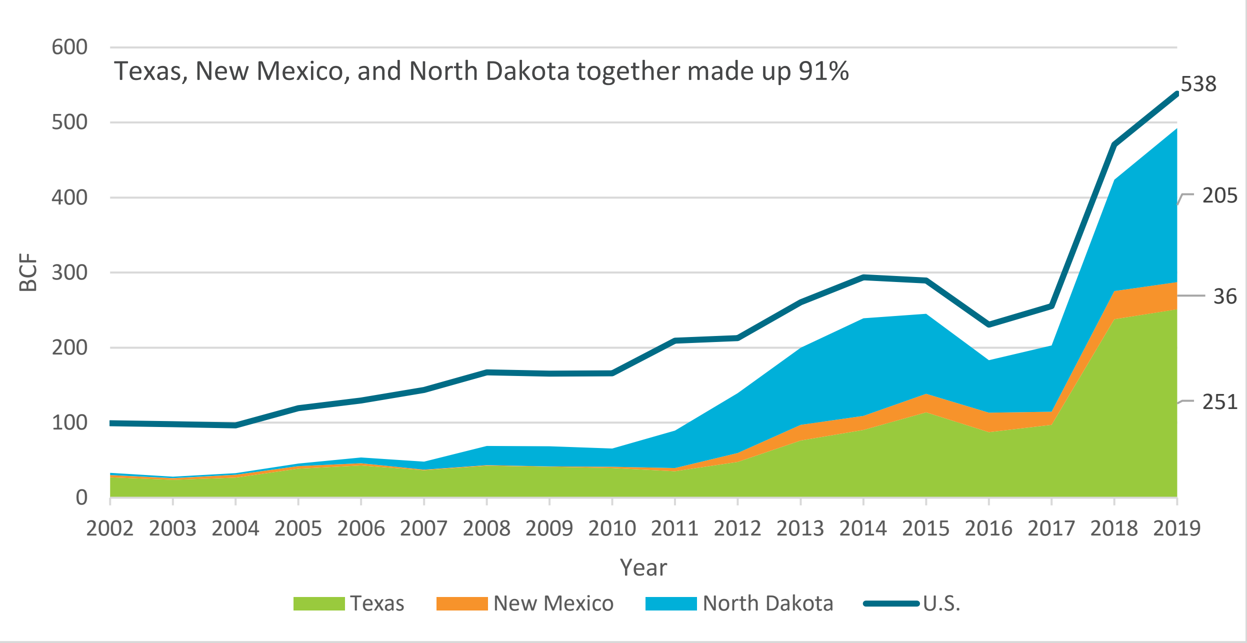
1.1 NATURAL GAS FLARING

Natural gas flaring is defined as the controlled combustion of natural gas for operational, safety, or economic reasons. [1] Venting is the direct release of natural gas into the atmosphere; it is often restricted by state regulators.

Natural gas flaring and venting for operational and safety reasons are generally short term and sometimes essential to routine production operations. On the other hand, flaring for economic reasons—which involves combusting associated gas obtained with crude oil—typically takes place over the complete life span of a producing well. The reason for such flaring is either a complete lack of, or inadequate, infrastructure for gathering, compression, and sales of the natural gas associated with oil production. [1]

A large volume of natural gas is stranded annually due to flaring for economic reasons. According to EIA, a total of 538 billion cubic feet (BCF) of natural gas was vented and flared in the United States in 2019 (Exhibit 1-1). [2] This amount was up by about 14 percent compared to 2018 volumes. Texas, North Dakota, and New Mexico contributed to more than 90 percent of this volume in 2019. In all these states, flaring was higher in 2019 compared to 2018.

Exhibit 1-1. U.S. natural gas vented and flared



Texas, New Mexico, and North Dakota together made up 91 percent of total natural gas volume flared in the United States in 2019.

In 2018, North Dakota, home to the Bakken shale (located within the Williston Basin) was one of the top three oil producing regions and was estimated to have the top three largest (onshore) reserves in the United States. The Permian Basin (spanning West Texas and Eastern New Mexico) and the Eagle Ford shale (Western Gulf Basin, Texas) constituted the two remaining ranked positions in the top three producing and estimated reserves list in 2018. Exhibit 1-2 summarizes 2018 flaring activity in the top three oil-producing basin/plays in 2018. [3]

Exhibit 1-2. Flaring activity in Permian, Eagle Ford, and Bakken plays in 2018

	Permian Basin	Eagle Ford	Bakken
Reporting Agency	**Texas Railroad Commission**	**Texas Railroad Commission**	**North Dakota Industrial Commission**
Total Annual Flared Volume (MMCF)	88,953	18,968	63,329
Total Annual CO_2 Emissions (MM ton)	5.67	1.61	5.23
Average Flaring Volume Per Flare (MCFD)	57.4	27.0	27.4
Top 3 Months with Maximum Flaring Volume Per Flare	October, November, December	August, September, October	September, October, November
Average Flaring Volume Per Flare (MCFD) in Top 3 Months	77.3	29.9	30.7

The Permian Basin had the highest annual flaring volume at around 88.9 BCF. The associated CO_2 emissions were also the highest at 5.67 million metric tons (MMT) per year. It is worth noting that even though the Bakken shale has a 30 percent lower annual flared volume than Permian Basin, its CO_2 emissions are lower by only 8 percent. That the molar concentration of carbon isotopes is higher in the gas extracted from Bakken (91.5 percent) compared to Permian (87 percent) may be one of the reasons for higher emissions. [3]

The average flaring volume per flare is 19.9 thousand cubic feet per day (MCFD) higher in October, November, and December compared to the yearly average. Persistent gas takeaway constraints and basin-wide increases in gas production are the main reasons for this trend in the last quarter of 2018. Unprecedented early-life flaring rates in the New Mexico side of the Delaware platform, and a large rise in production in the less-developed eastern Midland (Howard County) were the top reasons resulting in this trend in the Permian. [4] Such a stark change was not seen for the Eagle Ford and Bakken shale plays.

Exhibit 1-3 gives a breakdown of total volume of flaring activity by the size of each unit. [3] An estimate of relative flaring volumes by flaring unit size is made by dividing the 0.1–1,000 MCFD range into two categories: (i) less than 500 MCFD, and (ii) 500–1,000 MCFD. It is seen that in Eagle Ford, category (i) or smaller flares contribute to around 86 percent of the total flaring volume. For the Permian Basin and the Bakken, these percentages are 75 percent and 58 percent, respectively.

Exhibit 1-3. Volume flared in 2018, by flare size

BAKKEN

Flare Size (MCFD)	Flare Units	Total Volume (MCFD)
<=100	3,781	99,761
100-200	753	109,036
200-300	442	109,508
300-400	280	96,755
400-500	206	92,716
500-600	149	81,686
600-700	140	91,261
700-800	98	73,091
800-900	83	70,739
900-1,000	58	54,669

PERMIAN

Flare Size (MCFD)	Flare Units	Total Volume (MCFD)
<=100	44,252	601,057
100-200	2,401	339,660
200-300	1,105	269,029
300-400	596	205,937
400-500	366	163,629
500-600	240	131,329
600-700	203	131,534
700-800	146	108,801
800-900	99	84,003
900-1,000	73	68,990

EAGLE FORD

Flare Size (MCFD)	Flare Units	Total Volume (MCFD)
<=100	21,825	253,474
100-200	659	91,092
200-300	210	51,644
300-400	96	33,560
400-500	58	26,053
500-600	35	19,108
600-700	26	16,528
700-800	16	11,903
800-900	19	16,139
900-1,000	11	10,125

Historically, there has been a discrepancy in reported flaring volumes. DOE's *Natural Gas Flaring and Venting report* from the Office of Fossil Energy and Carbon Management and Office of Oil and Natural Gas points out this dissimilarity between EIA and National Oceanic and Atmospheric Administration (NOAA)[b] data for the period 2012–2017 for New Mexico, North Dakota, and Texas. Exhibit 1-4 shows the comparison with a few updates to EIA data in later years (2019 was the latest year for which EIA and NOAA flaring data were available, by state). This data is compiled by S&P Global Market Intelligence (SPGMI) Platform. [1] [5]

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[b] NOAA collected and curated flaring data from point sources using Earth Surveillance Systems for the period 2012–2017. The results should be accurate within plus or minus 9.5% of the actual flared gas volume.

Exhibit 1-4. Comparison of volumes of natural gas flared in selected states (BCF)

Year	New Mexico		North Dakota		Texas	
	NOAA/Other Sources[A]	EIA[B]	NOAA/Other Sources[A]	EIA[B]	NOAA/Other Sources[A]	EIA[B]
2012	14	12	142	80	125	48
2013	24	21	111	103	142	76
2014	31	19	136	130	182	90
2015	42	25	125	107	204	114
2016	31	26	80	70	160	88
2017	23	17	114	89	163	97
2018	41[A]	37	183[A]	149	229[A]	238
2019	40[A]	36	215[A]	205	317[A]	251

[A] A collaboration between SPGMI and the Earth Observation Group at the Payne Institute of Public Policy, Colorado School of Mines.

[B] EIA reports a single dataset for venting and flaring. This may cause some EIA cells to have a bigger value than flaring-only data from satellites; these come from states with some amount of venting activity in addition to flaring.

While discrepancies between EIA reporting and NOAA-detected flared volumes is seen for each state during 2012–2017, the differences are the most glaring for Texas with NOAA-volumes around two times greater than the EIA data.[c] The Environmental Defense Fund (EDF) also conducted such a study with satellite data and came to similar conclusions for the year 2017. [1] [6] However, its claims have been refuted by the officials at Texas Railroad Commission (TRRC). Energy in Depth, a campaign funded by the Independent Producers Association of America, points out that EDF's methods rely only on top-down approach for data collection from subsets of Permian Basin and state-owned University Lands. Energy in Depth also mentions that getting an accurate measure of flaring would require a bottom-up approach in addition to top-down. [1] [7]

On a national level, flaring volumes reduced by 32 percent in 2020 due to two factors: a drop of 8 percent in oil production due to the global coronavirus pandemic, and new infrastructure to transport associated gas.[d] [8] EIA's *Short-Term Energy Outlook*, based on data from the first quarter of 2021, forecasts a global consumption growth of petroleum and other liquid fuels by 5.3 MM barrels/day following a year-on-year decline of 8.6 MM barrels/day in 2020. The United States would be the biggest contributor to this rise at 1.5 MM barrels/day growth over 2020. Non-Organization of the Petroleum Exporting Countries production is also forecasted to rebound with a rise of 1.1 MM barrels/day in 2021 and 3.1 MM barrels/day in 2022. [9]

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[c] DOE considers many datasets; however, it establishes baselines through EIA data.

[d] The World Bank's Global Gas Flaring Reduction (GGFR) is a trust fund and partnership of governments, oil companies, and multilateral organizations working to end routine gas flaring at oil production sites around the world. GGFR, in partnership with NOAA and the Colorado School of Mines, has developed global gas flaring estimates based upon observations from two satellites, launched in 2012 and 2017. The advanced sensors of these satellites detect the heat emitted by gas flares as infrared emissions at global upstream oil and gas facilities.

1.1.1 Emissions Data and Environmental Impact

The activities of venting and flaring release GHGs such as methane and CO_2 in the atmosphere. Methane emissions from gas flaring contribute significantly to global warming in the short to medium term because methane has a global warming potential that is over 80 times higher than CO_2 on a 20-year basis. [8]

Exhibit 1-5 shows the CO_2 and methane emissions due to flaring associated gas in 2019. [10] The Williston Basin (where Bakken Shale is a located) is the biggest contributor to GHG emissions in 2019.

Exhibit 1-5. Associated gas flaring national GHG emissions in 2019

Source	CO_2 emissions (MMT CO_2)	CH_4 emissions (MMT of CO_2e)
Gulf Coast Basin (LA, TX)	0.58	0.07
Williston Basin	16.57	1.21
Permian Basin	7.16	0.68
Anadarko and Other Basins	1.04	0.09
Total Emissions	**25.35**	**2.05**

The total emissions from associated gas flaring in 2019 made up 0.53 percent of energy-related CO_2 emitted in the United States (5,130 MMT). [11] These total emissions from flaring are comparable to GHG emissions from bus transportation sector in 2019 (22.2 MMT CO_2e) and the industrial production of petrochemical products like carbon black, ethylene, and methanol (31.1 MMT CO_2e). [10] Based on EPA's GHG equivalencies calculator, the total emissions from flaring are equivalent to CO_2 emissions resulting from 1-year electricity use by around 5 million homes. [12]

The numbers shown in Exhibit 1-5 present one of the estimates for emissions from flaring. There are challenges with getting a single estimate on emissions that can be relied upon by all groups stemming from issues like data discrepancies and differing opinions on curations methodologies. Some studies from environmental groups question assumptions made by EPA in curating its data. One such example is EDF's PermianMAP Initiative.[e] According to EDF, EPA assumes that operators flare gas at 98 percent efficiency, but it may be as low as 93 percent, meaning that at least 7 percent of methane escapes directly to the atmosphere. [13] Additionally, EDF found that 11 percent of the flares in their study area in Texas were malfunctioning, either venting methane or only partially combusting it before releasing into the atmosphere. [13] The accuracy of these claims has been questioned by state government officials at TRRC and Energy in Depth. [7]

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[e] The Permian Methane Analysis Project (PermianMAP) is an initiative that combines data collection from air (flights), towers (using sensors) and on the ground (mobile vehicles) to pinpoint, measure and report on oil and gas methane emissions in a study area of the Permian Basin.

There is a potential to make a considerable environmental impact in terms of avoided emissions by 2050 if such natural gas were upcycled into higher value, carbon-based products. As per EIA's *Annual Energy Outlook 2021*, the volume of dry natural gas production in 2050 is projected to be close to 43 trillion cubic feet in the reference scenario. [14] Back-calculating annual vented/flared volume from projected dry gas based on the 2019 volume of dry gas produced from oil formations, [15] [16] finds the annual flaring volume in 2050 could lie at 323–751 BCF. Converting this to emissions, there is a potential to avoid 17.14–39.86 MMT CO_2 in 2050 by upcycling natural gas into products.[f]

There was improvement in 2020, in terms of reduced flaring. According to a recent report based on NOAA data by the World Bank's Global Gas Flaring Reduction (GGFR) Partnership, there was a five percent decrease, globally, in flaring in 2020. The largest single contributor was a 32 percent decrease in flaring activity by U.S. oil and gas producers. [17] This decrease can be attributed to falling oil production, combined with the completion of the Gulf Coast Pipeline carrying gas out of the Permian Basin. The United States is an endorser of World Bank's recently launched "Zero Routine Flaring by 2030" initiative alongside several other governments and international organizations. As per this initiative, governments will stipulate in their new prospect offers, that field development plans for new oil fields incorporate sustainable utilization or conservation of the field's associated gas without routine flaring (or flaring for economic reasons). The focus here would be on developing markets for such gas and to provide a conducive environment for upstream investments to develop necessary infrastructure to deliver gas to markets.

1.1.2 Regulatory and Other Actions to Reduce Venting and Flaring

The economics of deploying options to avoid flaring often do not justify the investment; this is when regulatory and/or policy intervention becomes necessary. This section discusses the regulations on flaring and/or venting in Texas and North Dakota (the two states making up almost 85 percent of the vented/flared volume in the United States in 2019).

In Texas, the TRRC has jurisdiction over flaring. It issued more than 10 times the flaring permits in the 2016–May 2018 timeframe than in 2008–2010. [1] Most permit requests are for casinghead (or associated) gas, 45 days at a time, for a maximum limit of 180 days. The most common reason for granting an extension to an initial flaring permit is when the operator is waiting for scheduled pipeline construction to be completed by a specified date. Current law exempts flared gas from oil wells from the state's 7.5 percent natural gas production tax. [1]

In November 2020, TRRC Commissioners approved a *revamped Form R-32, Application for Exception to Statewide Rule 32,* which will, in many cases, reduce the period for which an operator may request exception to flare gas. [18] Other changes, like incentivizing use of flare-reducing technologies, requiring stricter justifications from operators to flare/vent gas, and more robust data reporting for compliance audits, are also included. [18]

Some companies are making efforts by restricting production or building the infrastructure needed to gather the natural gas. In March 2020, a voluntary coalition of companies and

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[f] Please refer to Appendix A: Environmental Impact Calculations for calculations.

organizations formed the Texas Methane and Flaring Coalition comprising 40 oil and natural gas companies and industry groups like the Permian Basin Petroleum Association and the Texas Oil and Gas Association. The Coalition will evaluate existing data and evidence on flaring and methane emissions from the industry in Texas and will develop opportunities and recommendations to continue to minimize these practices. [1] [19]

Presently, North Dakota has a ban on venting. The North Dakota Industrial Commission (NDIC) established *Order No. 24665 (2014)* as a system of gas capture requiring producers to submit a gas capture plan with every drilling permit application. [1] The latest change to Order 24665 happened in November 2018 when NDIC decided to focus more on incentivizing gas capture than reducing flared volume. [1] The goals were to capture 85 percent associated gas between November 1, 2016, and October 31, 2018; 88 percent between the next two years; 91 percent beginning November 1, 2020. [1] However, eleven companies captured less than 85 percent in September 2018. [1] [20] Of the flared volume, 75 percent comes from the wells with some gas transport infrastructure and 25 percent comes from those with a complete lack of pipeline access. [1] [21] Expansion of both natural gas processing and natural gas liquids pipeline takeaway capacity are essential to reducing flaring in North Dakota. [1]

1.2 HIGH-VALUE CARBON PRODUCTS FROM NATURAL GAS

1.2.1 Material Balance & Quantification of Products

To calculate the amount of carbon available from vented and/or flared gas, it is necessary to know the composition of different molecules within the produced natural gas. This can be done by leveraging the 2018 NETL flaring reports from the Bakken shale, Permian Basin, and Eagle Ford shale, and then creating a weighted average from those three reservoirs to forecast the composition of the remaining vented/flared natural gas. The ideal gas law equation is then used to convert the volume of gas into moles of gas that can be multiplied by the mole balance for each respective resource. Once the total moles vented/flared for each hydrocarbon in the natural gas is known, a stoichiometric balance can be performed to know the total amount of carbon and hydrogen that could be generated, assuming all the natural gas that would have been vented/flared was reacted to completion (Exhibit 1-6).

Exhibit 1-6. Stoichiometric balance results: carbon and hydrogen

Reservoirs	Carbon (metric tons)	Hydrogen (metric tons)
Permian	492,192	82,025
Bakken	414,898	69,150
Eagle Ford	127,463	21,244
Other*	2,227,581	371,264
Total	3,262,093	543,682

*Other represents the remaining amount of flared natural gas in the United States, [2] which is not flared from either Permian, Bakken, or Eagle Ford.

Using the material balance and assuming that all of the vented/flared natural gas was reacted to completion, over 3.25 MMT of carbon would have been produced in 2019 in the United States. This large volume production potential of carbon creates an opportunity to enter any of the carbon product markets considered in this report, even if only a fraction of the natural gas vented/flared is converted into the carbon products.

Hydrogen has been emphasized as a potential energy source to aid in decarbonization efforts. The added benefit of using vented/flared natural gas to produce carbon products is that hydrogen gas is a natural byproduct of the reaction. By following the same methodology but calculating the stoichiometrically balanced amount of hydrogen created from the vented/flared natural gas, there is the potential to create over 540,000 metric tons of hydrogen based on vented/flared volumes in 2019. While this study primarily focuses on the market and potential for carbon products created, the added benefit of creating a high volume of hydrogen gas should not be undervalued when considering whether this technology should be pursued. If transportation logistics prove to be too costly to transport the hydrogen away from the wellsite, the hydrogen can also be used as a potential energy source on the wellsite.

2 TECHNOLOGY OVERVIEW

2.1 STEAM METHANE REFORMING

In order to properly evaluate the opportunity for technology application, it is important to understand the primary technology used for repurposing natural gas. Steam methane reforming (SMR) is a commercially available industrial process that separates a hydrocarbon source into hydrogen and carbon. As shown in Equation 1 and Equation 2, natural gas is pre-heated, mixed with high-temperature steam (700–1,000°C) to produce hydrogen and, ultimately, CO_2. SMR is the most cost-effective method to produce hydrogen, resulting in 95 percent of all hydrogen produced in the United States; [22] however, the reaction does not provide the added benefit of capturing solid carbon as a product. SMR is not a viable solution in reducing the carbon footprint through the repurposing of natural gas as it still releases CO_2 through the process. The technologies discussed in this section are effective alternatives that can utilize the natural gas without leaving a carbon footprint.

$$CH_4 + H_2O\ (+heat) \rightarrow CO + 3H_2$$

Equation 1. Steam methane reforming reaction I

$$CO + H_2O \rightarrow CO_2 + H_2\ (+small\ amount\ of\ heat)$$

Equation 2. Steam methane reforming reaction II

2.2 METHANE PYROLYSIS

Methane pyrolysis is the practice of using high heat to break down the natural gas into its base elements of carbon and hydrogen and serves as a potential pathway toward solid carbon feedstock production. Instead of requiring an additional reactant like the water in SMR, pyrolysis is the decomposition of the natural gas and requires no additional reactants as seen in Equation 3. Methane and the other natural gas hydrocarbons are stable molecules and through the addition of 1,100–1,200°C heat, they can be forced to decompose into hydrogen and pure carbon. [23] The high reaction temperature required to decompose the hydrocarbons within the natural gas leads to process inefficiencies, thus higher costs for lower conversion yields.

$$\boldsymbol{CH_4 \rightarrow C(s) + 2H_2}$$

Equation 3. Methane pyrolysis reaction

The inclusion of catalysts in the pyrolysis reaction is an important factor to lower the temperature requirements for the hydrocarbons to properly decompose. The most common catalysts that are being researched and tested today are transition metals, carbon catalysts, and molten metals.

2.2.1 Transition Metals

Transition metals like nickel, iron, and cobalt have a comparatively high catalytic activity, which lowers the temperature for reaction. By using transition metals as a catalyst there is also the possibility of producing carbon nanotubes (CNTs) as a byproduct at the activation site. [24] An added complication of using transition metal catalysts is the requirement of a regeneration process to separate the carbon from the metal catalysts, which leads to partial oxidation of the carbon. As of 2021, no technologies including transition metal catalysts have been used on an industrial level, and will require improvements to carbon regeneration techniques to see adoption. [23]

2.2.2 Carbon Catalysts

Carbon catalysts have a lower activity compared to transition metals, requiring reaction temperatures of 800–1,100°C. Despite higher energy costs for a catalyst reaction, carbon catalysts have many comparative advantages, namely lower material cost, greater temperature stability and resistance, higher tolerance to impurities within the natural gas, and no needed catalyst regeneration. Additionally, the produced carbon has the potential to act as a catalyst during the remainder of the reaction of the process. [23] Currently, this technology is still at the research level as there are uncertainties of the process mechanics. Primarily, there is a need for greater understanding of the reaction mechanism in order to improve the catalyst activity, as well as further research on the correlation between the carbon structure and the role it plays as a catalyst. [25] In order to reach an industrial- or even pilot-scale for carbon catalyzed methane pyrolysis, research will be necessary to better understand the reaction mechanics.

2.2.3 Molten Metals

Molten metals have been a topic of interest over the past ten years as another potential process to decompose natural gas without oxidizing the carbon. The process uses molten metals like nickel, palladium, or platinum, alongside molten metal alloys and molten salts in a liquid bubble column to effectively pyrolyze the natural gas. [26] The reactions occur within the bubbles of the column and the solid carbon rises above the molten metal as the carbon has a lower density. As the carbon and hydrogen naturally separate, this allows the molten metal to be continuously renewed as a catalyst in the reaction and reduces the risk of catalyst corrosion and contamination. [27]. As of the time of this report, there are still challenges that prevent this technology from reaching industrial scale, primarily the high temperature requirements for operation, greater than 1,000°C. With such a high temperature requirement, there are additional process challenges associated with finding a suitable molten media that can stably withstand the heat. [28]

2.3 OPPORTUNITIES AND CONSIDERATIONS

While methane pyrolysis has yet to be implemented on an industrial level, there are unique opportunities and key considerations when directly considering a future implementation in reducing otherwise vented/flared natural gas. It is important to consider what energy sources can be utilized to power the additional technology needed to thermally decompose the natural gas on the wellsite.

2.3.1 Recycling Hydrogen

In non-pyrolysis operations, such as those used to produce carbon black, the produced hydrogen is recycled back into the process to be used as a power source. [29] As different technologies continue to develop for methane pyrolysis, this same technique can be leveraged in new processes to help lower the external energy requirements for the reactions. This can also reduce costs across the supply chain if the hydrogen can be effectively consumed by avoiding storage and transportation costs.[g]

2.3.2 Natural Gas

Where it is deemed more beneficial to utilize the produced hydrogen elsewhere, the needed energy can be satisfied from the natural gas produced on the wellsite. By understanding the amount of natural gas that would have been vented/flared, process operations can calculate the correct proportion of the natural gas to be used as an energy source to effectively pyrolyze the remaining natural gas. This opportunity is considered less ideal than recycling the hydrogen as it produces less hydrogen and carbon product, and there will be a greater environmental footprint by using the natural gas that has been allocated as the energy source to convert the remaining gas into carbon.

2.4 CURRENT RESEARCH LITERATURE REVIEW

No pyrolysis technology is currently operating at an industrial scale. National laboratories, as well as privately-funded research projects approach the challenge from a wide range of possible solutions, as outlined in Exhibit 2-1. As the emphasis to approach carbon neutrality continues to grow, methane pyrolysis may become a greater opportunity and more institutes will allocate efforts to research how to optimize the technology. The most promising technologies will begin to emerge as the industry becomes more focused.

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[g] This is assuming that the hydrogen produced does not provide enough energy by itself to activate the pyrolysis reaction.

Exhibit 2-1. Current research initiatives

Research Institute	Research Name	Funding Institute	Technology Type	Carbon Products
PNNL/SoCal Gas/ WVU	Methane Pyrolysis for Base-Grown Carbon Nanotubes and CO_2-free H_2 over Transition Metal Catalysts	PNNL	Methane Pyrolysis using Fluidized Bed Reactor; Base-Growth on Ni Catalyst	CNTs
Palo Alto Research Center (PARC)	Using Molten Metal as a Catalyst for H_2 Production	ARPA-E	Methane Pyrolysis using Mist Reactor; Molten Metal as a Catalyst	None Specified
Johns Hopkins University	Electrothermal Conversion of Methane into Hydrogen and High-Value Carbon Fibers	ARPA-E	Methane Pyrolysis using Electrothermal Reactor	Graphitized Carbon Fibers from Low Quality Carbon Products (e.g., graphite particles)
Johns Hopkins University/Southern Company/Cabot	Carbon Dioxide-Free Hydrogen and Solid Carbon from Natural Gas via Metal Salt Intermediates	ARPA-E	Methane Pyrolysis without the use of Water	None Specified
NanoComp	High Value Energy Saving Carbon Products and Clean Hydrogen Gas from Methane	ARPA-E	Not specified	Miralon®
Rice University	From Hydrocarbon Feedstock to Recyclable Carbon-Based Automotive Bodies with Positive Hydrogen Output	ARPA-E	Not specified	CNTs
Stanford University	Co-Synthesis of Hydrogen and High-Value Carbon Products from Methane Pyrolysis	ARPA-E	Methane Pyrolysis	CNTs
Notre Dame	Process Intensification by One-Step, Plasma-Assisted Synthesis of Liquid Chemicals from Light Hydrocarbons	NETL	Plasma-Assisted Synthesis	Liquid Chemicals
PARC	Gas to Carbon Fiber Crystals (G2-CFX)	NETL	Methane Pyrolysis using Experimental Micro-Pulldown Crystal Fiber Reactor; Molten Nickel	Carbon Fiber
West Virginia Research Corp	Microwave Catalysis for Process Intensified Modular Production of Carbon Nanomaterials from Natural Gas	NETL	Methane Pyrolysis; Microwave Assisted Catalysis	CNTs & Carbon Fibers
University of Colorado	Modular Processing of Flare Gas for Carbon Nanoproducts	NETL	Methane Pyrolysis using Fluidized Bed Reactor & Chemical Vapor Deposition	Carbon Nanoparticles and Nanofibers
Hazer Group/University of Sydney	The Hazer Process	N/A (Private)	Methane Pyrolysis using Fluidized Bed Reactor; Iron Ore Catalyst	Graphite

3 PRIMARY CARBON PRODUCTS

This section provides definitions for the four carbon products selected for analysis in this report and discusses how their individual molecular structure leads to differences in application.

3.1 CARBON FIBER

Carbon fiber is a form of crystalline carbon made up of interlocking sheets of graphene, which, in turn, are made up of carbon atoms. Such fibers exist at the scale of micrometers (10^{-6}m in diameter). [30] Carbon fibers offer various advantages such as high tensile strength, low weight, high stiffness, high-temperature tolerance, and low thermal expansion. [31] They are used primarily as a reinforcing agent in high-performance composites with synthetic resin matrices.

3.1.1 Raw Materials for Carbon Fiber

About 90 percent of carbon fiber is produced from the precursor polyacrylonitrile (PAN). The remaining 10 percent is made using either petroleum pitch or rayon. Choice of raw material dictates the properties of the carbon fiber end-product. A summary of provided in Exhibit 3-1.

Exhibit 3-1. Properties and uses of carbon fiber by raw material

Precursor	Properties of Resulting Carbon Fiber	Uses
PAN	High tensile strength and elastic modulus	Structural material composites in aerospace & defense, industrial, and sporting goods
Pitch	Ultra-high elastic modulus leading to high thermal and electrical conductivity	Aerospace and sports industries
Rayon	Low thermal conductivity, high electrical conductivity	Aerospace (rocket nozzle, missile re-entry vehicle nose cones, and heat shields) and defense (research on ablation performance)

"Vapor-grown" carbon fiber from hydrocarbon gases like methane (which is the main component of natural gas) is known for a fundamentally ultra-high modulus. [32] Unlike the complex PAN-based process, the manufacturing process for vapor-grown technology is simpler, faster, and cheaper. [33]

The total market size for PAN-based carbon is about 6 billion pounds, out of which only about 30 million pounds are used as a precursor for carbon fiber. The price of PAN depends on the price of crude oil.

3.2 CARBON NANOTUBE

Nanotubes consist of carbon atoms bonded to one another in repeating hexagonal patterns to create a hollow cylinder. Each CNT is only one nanometer in diameter. [30] Each tube may by formed by rolling up a single sheet of graphene (single-walled carbon nanotubes [SWCNTs]) or by rolling up multiple sheets of graphene (multiwalled carbon nanotubes [MWCNTs]). All applications make use of a nanotube's electrical and thermal conductivity.

Carbon fiber is turbostratic, meaning flat layers, each one a single carbon atom thick, stacked somewhat haphazardly on top of one another. In contrast, a nanotube has a neatly organized, tightly bonded configuration. The CNT's superior atomic-bonded crystal structure makes it nearly 20 times stronger per pound than carbon fiber. [34] With increased focus on research and development of CNT composites, it is likely that such nanocomposites will replace carbon fibers as superior substitutes. However, nanotube composites are still in the research phase. [31]

3.3 SYNTHETIC GRAPHITE

Graphite is a semi-metal, crystalline carbon in which carbon atoms are densely arranged in parallel-stacked, planar honeycomb lattice sheets. Synthetic graphite is manufactured from amorphous carbon precursors, which may be derived from petroleum, coal, or natural and synthetic organic materials. [35] It is a purer form of graphite than natural graphite, hence, more expensive. Due to its predictable behavior, it is used in high-end applications like solar battery and electric-arc furnaces. [36]

3.4 CARBON BLACK

Carbon black is most frequently a byproduct from the incomplete combustion of heavy petroleum products. It is a paracrystalline product, meaning that the ordering of lattices is shorter than graphite and synthetic graphite, which contributes to its powder form. Carbon black is most commonly used as a reinforcing agent for rubber tires and as a color pigment in coatings or printer inks and toners, or as conductive filler material for inks or plastics.

4 MARKET ANALYSIS

4.1 CARBON FIBER

Carbon fiber is a product known widely for its fiber-composite applications in the aerospace and defense, automotive, wind energy, and sporting goods industries. This section discusses such applications, market size by different segments like end-use industry, product type, and region; cost to manufacture; opportunities and barriers to market growth; and a note on recycled carbon fiber. Unless otherwise stated, all information in this section comes from MarketsandMarkets's *Carbon Fiber Forecast to 2025*. [31]

4.1.1 Market Overview

4.1.1.1 End-Use Applications

Carbon fiber can be divided into two main application categories: composite and non-composite. A composite material is different from non-composite in that it contains at least two constituent components: a reinforcement (like carbon fiber), and a matrix (like epoxy polymer). The matrix binds reinforcement together to merge the benefits of both original components. [37]

The composite carbon fiber segment accounted for 93.3 percent of market share by value in 2018. Prepreg[h] is the most widely used composite, available in the form of thermoset US-, thermoset fabric- and thermoplastic-prepregs. It accounted for more than 83 percent of the composite carbon fiber market by value in 2019. North America and Europe are the major consumers of this composite. Molding compound[i] is another key composite application used in automotive and wind industries for its impact strength, dimensional stability, corrosion resistance, and high stiffness. Finally, woven fabric[j] is a slightly different composite application, used in boat construction, sporting goods, and orthopedic parts, etc.

Non-composite applications of carbon fibers constitute an emerging market. Some of the more prominent applications are catalysis, electrodes for batteries, and 3D printing. PAN-based nano carbon fibers are used to catalyze production of synthetic gasoline. Using carbon fiber as an anode in batteries can result in considerable improvements like prolonged life cycles (which makes them eligible for use in electric vehicles), overall battery weight reduction, and enhanced discharge rate. Some of the major carbon fiber 3D printers include Fusion F410[k] and Raise3D Pro2 Plus.[l]

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[h] Prepreg is a common term for a reinforcing fabric that has been pre-impregnated with a resin system, typically epoxy resin. (For more information, visit https://www.fibreglast.com/product/about-prepregs/Learning_Center.)

[i] Carbon Fiber Molding Compound is a polymer composite reinforced with chopped carbon fibers.

[j] Woven Fabric uses strands of carbon fiber with an epoxy resin lamination matrix.

[k] Fusion F410 is a professional grade 3D printer designed, manufactured, and supported in the United States. (For more information, visit https://www.fusion3design.com/.)

[l] Raise3D is a leading manufacturer of industrial-grade 3D printers with headquarters in the United States, Europe, and Asia. (For more information, visit https://www.raise3d.com/why-raise3d/.)

4.1.1.2 Market Size

The carbon fiber market can be segmented by product type into three categories: continuous fiber, long fiber, and short fiber. Most of the high-end applications use the continuous fiber type. Refer to Section 4.1.3 for a range of prices for continuous fiber.

Continuous fiber, known for its high tensile strength, is used in processes like prepregging, braiding, and pultusion for manufacturing composite parts. Presence of aircraft giants like Boeing and Airbus drive market growth in Europe and North America, which jointly hold more than a 70 percent share in the continuous fiber market.

Long carbon fiber is used mostly as composites in sporting goods because of properties like load-carrying ability, dimensional stability, and consistent performance over a range of temperatures. The Asia Pacific (APAC) region led the long carbon fiber market, by value, in 2018 by accounting for 39.3 percent share. APAC's combined annual growth rate (CAGR) for 2019–2024 is 7.5 percent.

Short carbon fiber is useful for industrial mixing and compounding processes, and for making materials electrically conductive. It is known for properties like low density, low thermal expansion, and non-corrosion. Like long carbon fiber, APAC dominates the short carbon fiber market with a huge share of 58 percent by value. A CAGR of 7 percent (2020–2025) is attributable to growing electrical and electronics industry in APAC.

The market size by value and volume of each of these categories is presented in Exhibit 4-1. It is seen that continuous carbon fiber holds the maximum share in terms of market value and volume; it also has the highest CAGR of 11.0 percent by value in 2020–2025. It is used extensively in Aerospace-Defense and Automotive Industries for its high strength and rigidity.

Exhibit 4-1. World: carbon fiber market size by product type

Product Type	Market Size ($MM USD)			Market Size (kiloton)		
	2019	2020	CAGR (2020–2025)	2019	2020	CAGR (2020–2025)
Continuous Carbon Fiber	4,327.0	3,737.6	11.0%	91.9	80.5	11.6%
Short Carbon Fiber	260.4	232.7	7.5%	10.1	9.1	8.0%
Long Carbon Fiber	183.0	160.0	8.6%	6.5	5.8	9.1%
Total	4,770.4	4,130.3	10.7%	108.6	95.4	11.2%

Looking at the industrial level, carbon fibers have been traditionally used in aerospace and defense industries for their exceptional mechanical and physical properties like strength-to-weight ratio, and heat resistance. These industries continue to have the biggest share (~64 percent by value) in market demand. More recently, many other industries have shown an increase in carbon fiber demand; these include automotive and wind energy with 2020–2025 CAGRs 15.4 percent and 12 percent, respectively. These are presented in Exhibit 4-2. The growth in automotive consumption is driven by big players like BMW, Audi, and Toyota, who are inclined to use carbon-fiber derived composites in their vehicles.

Exhibit 4-2. World: carbon fiber market size by end-use industry

End-Use Industry	Market Size ($MM USD)			Market Size (kiloton)		
	2019	2020	CAGR (2020–2025)	2019	2020	CAGR (2020–2025)
Aerospace & Defense	3065.2	2612.3	10.8%	32.1	27.3	11.30%
Automotive	421.8	337.0	15.4%	19.3	15.5	16.00%
Wind Energy	355.6	337.3	12.9%	15.5	14.7	13.50%
Sporting Goods	297.2	273.0	6.2%	11.5	10.6	6.70%
Electrical and Electronics	150.7	138.4	7.0%	5.2	4.7	7.00%
Civil Engineering	104.2	93.6	6.5%	4.7	4.2	7.80%
Pipe & Tank	99.2	87.1	7.3%	2.7	2.6	8.00%
Marine	59.1	56.1	7.5%	8.4	7.7	7.50%
Others	217.4	195.4	9.0%	9.1	8.2	9.50%
Total	4770.4	4130.3	10.7%	108.6	95.4	11.20%

The market-share rankings stay the same while considering carbon fiber end-use industry market by volume. This is due to the large consumption by aircraft manufacturing giants like Airbus, Boeing, and Lockheed Martin. Fifty percent of Airbus XWB and Boeing 787 airframes are carbon fiber composite, which allow for operational economy by cutting fuel consumption, increasing cabin comfort, allowing less complex designs compared with traditional metal structure, reducing air drag, providing low radar observability (defense application), and increasing resistance to speed-induced high temperatures. Other end-use industries like sporting goods, electrical and electronics, and civil engineering (reinforced concrete) also drive growth in demand for carbon fiber.

Even in the United States, aerospace and defense and automotive are the leading sectors in carbon fiber market, by both value and volume. The primary drivers for this are aircraft companies venturing into all-composite construction, the use of carbon-fiber bodies for rockets and space vehicles, and mergers between prominent automotive players. The obligation of U.S. automakers to meet Corporate Average Fuel Efficiency (CAFE) standards of 54.4 mpg by 2025 by reducing weight of vehicles is also responsible for use of fiber in the automotive industry.

Exhibit 4-3 shows carbon fiber market size by five regions: Europe, North America (United States, Canada, and Mexico), APAC, Middle East and Africa, and South America. Europe and North America will continue to lead the carbon fiber market by accounting for more than 75 percent by value and 68 percent by volume, of the projected market share in 2025. In addition to the aerospace and defense, an uptick in offshore wind turbine installations in the last five years, and a strong presence of automotive manufacturers like BMW, Fiat, and Bentley—which make infrastructural use of carbon fiber composites—are the reasons for Europe's lead in the market. The market size for Middle East and Africa, and South America is very small compared to the top two regions.

Among North American sub-regions, the United States will account for the highest carbon fiber market share by value (~88 percent) and volume (~88 percent) in 2025. It will also see the highest CAGR of 11 percent in 2020–2025. High demand for carbon fiber structural composite parts in automotive, aerospace, wind energy, marine, etc., industries drives this market share.

Exhibit 4-3. World: carbon fiber market size by region

Region	Market Size ($MM USD)			Market Size (kiloton)		
	2019	2020	CAGR (2020–2025)	2019	2020	CAGR (2020–2025)
Europe	1895.7	1627.8	10.4%	42.2	36.4	11.0%
North America	1764.5	1504.9	10.8%	33.5	29.1	11.5%
APAC	878.9	794.2	11.4%	27.6	25.1	12.0%
Middle East and Africa	131.8	116.4	8.4%	3.2	2.8	8.9%
South America	99.5	86.9	9.3%	2.2	1.9	9.8%
Total	4770.4	4130.3	10.7%	108.6	95.4	11.2%

Looking at segmentation by region, by raw material, Europe dominates the PAN-based carbon fiber market in terms of value and volume. This is due to the increasing use of small tow[m] carbon fibers in high-performance aerospace and defense and automotive applications in the region. North America is the second largest and the fastest-growing market. North America and Europe accounted for more than 70 percent share of the pitch-based carbon fiber market. The pitch-based carbon fiber market is projected to grow at higher rates due to the increased use in applications such as braking materials in racing cars, airplanes, and golf club shafts.

4.1.1.3 Leading Producers

There are significant opportunities in the carbon fiber market; hence, producers aim to increase their share through mergers, acquisitions, and heavy investments in research and development to maintain a competitive advantage. Most of these activities are undertaken by a select number of leading producers indicated in Exhibit 4-4.

Exhibit 4-4. Leading producers of carbon fiber-based materials

Rank (Carbon Fiber Manufacturing)	Company Name	Based of Operations	Size of Business Segment pertaining to Carbon-Fiber (MM USD)	Carbon Fiber-Related Developments During 2017-April 2021
1	Toray Industries Inc.	Japan	2,409	Expansions, New Product Launches
2	Teijin Limited	Japan	<2,964 (Materials segment)	Expansion, Agreements, New Product Launches

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[m] A tow is a bundle of thousands of continuous individual carbon filaments held together and protected by an organic coating. Each carbon filament in a tow is a continuous cylinder with a diameter of 5–8 micrometers and consists almost exclusively of carbon.

Rank (Carbon Fiber Manufacturing)	Company Name	Based of Operations	Size of Business Segment pertaining to Carbon-Fiber (MM USD)	Carbon Fiber-Related Developments During 2017-April 2021
3	SGL Group	Germany	480	Partnerships, New Product Launches, Investment & Expansion
4	Mitsubishi Chemical Corporation	Japan	Unknown	Merger & Acquisition, Investment & Expansion
5	Hexcel Corporation	United States	315	Expansion, Acquisition, Joint-Venture, Product Launch
6	Formosa Plastics Corporation	Taiwan	Unknown	N/A
7	Solvay	Belgium	<3,060	Expansions and Partnerships
8	Jiangsu Hengshen Co. Ltd.	China	Unknown	New Product Development and Agreements on Increased Composite Material Use
9	Dowaksa	Turkey	Unknown	N/A
10	Hyosung	South Korea	Unknown	Investment and Expansion

* Revenue for all business segments of the company, including carbon fiber.

Due to the carbon fiber market being highly capital intensive, some aircraft and automobile companies also partner directly with manufacturers. For instance, in October 2016, Hexcel Corporation extended its existing agreement with Airbus Group. Under the agreement, Hexcel Corporation would supply HexPly M21E/IMA carbon fiber-based prepreg for the primary structures of Airbus A35OXWB aircraft. Established partnerships like these exist to customize end-user needs; this leaves less opportunity for new entrants in the market.

4.1.1.4 Notable Innovations within Market

Patterns in patents filing can reveal important innovations in the carbon fiber market. In 2018–2020, 9,055 patents were published with an upward trend in the number of filings per year. China accounted for the maximum number of patents filed at around 84 percent of all patents in 2018–2020.

Some of the top players in patent filing are the same as the leading carbon fiber producers. Exhibit 4-5 shows some of the major filers in 2018–2020.

Exhibit 4-5. Patents published by major players, 2018–2020

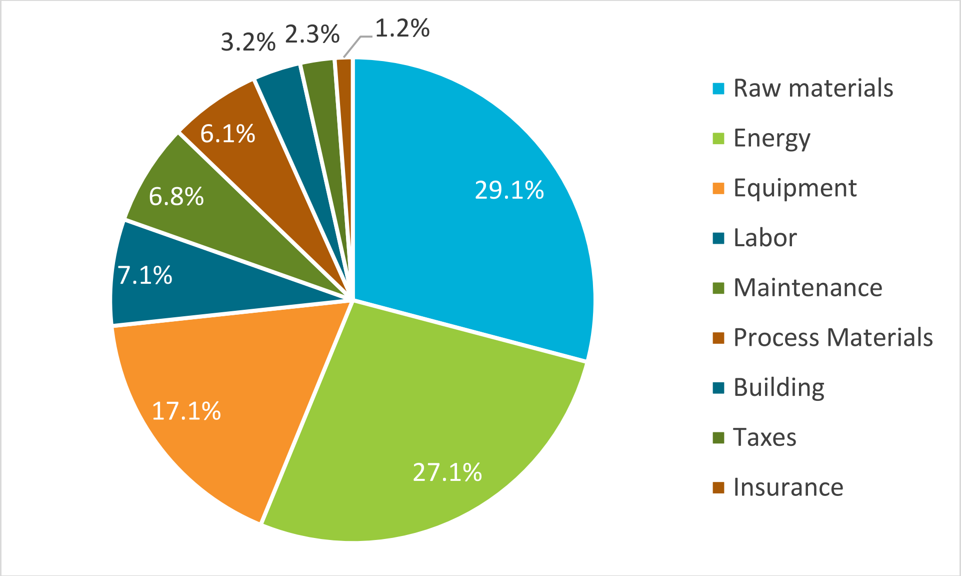
Name of Patent Filer	Number of Patents Published
Toray Industries Inc	78
Hengshen Company Ltd.	70
Anhui Xusheng New Material Company Ltd.	67
Beijing University of Chemical Technology	58
China Petroleum and Chemical Company	52
Dalian University of Technology	46
Datong Xincheng New Material Company Ltd.	45
LG Chemical Ltd.	44
Shandong University	44
Mitsubishi Chemical Holdings Company	42

The topics of some of the recent patents include sheet molding compound, carbon fiber production methods, instruments for handling different fiber materials like a yarn spreading device, automobile cover plate, wire structure optimization system, and plate processing and anchoring devices. Moreover, there are patent-topics like preparation methods for composite materials, optical fibers, and other products (like carbon-fiber plates).

4.1.2 Cost to Manufacture

Manufacturing accounts for the biggest share equaling 53 percent in the overall carbon fiber product cost. This 53 percent is broken down into manufacturing components as shown in Exhibit 4-6.

Exhibit 4-6. Carbon fiber manufacturing cost breakdown



The cost of raw materials and energy input together account for 56.2 percent of manufacturing costs. Carbon fiber is a result of multiple capital-intensive manufacturing processes like carbonization and stabilization. Since energy input plays a major role in their capital costs, lower energy prices can lead to significant cost reduction.

4.1.3 Pricing Estimate

As seen in Section 4.1.2, the cost of raw materials and energy input are major factors in determining the cost of the final fiber. Consequently, the end-user prices are affected by them. In addition, the prices are also affected by the modulus (standard, intermediate, high), carbon fiber filament count (small or large tow), and final product type (continuous filament, prepreg tape, etc.) [38]. Exhibit 4-7 below indicates average prices for continuing customers of PAN-based carbon fiber in the 12–48K filaments per-tow range.

Exhibit 4-7. U.S. market prices for PAN-based carbon fibers (USD/kg)

Year	Large-Tow Filament Standard Modulus (48K)	12–24K Continuous Filament		
		Standard Modulus (12K)	Intermediate Modulus (12K and 24K)	High Modulus (12K and 24K)
2009	18–33	22–35	53–106	88–154
2013	18–27	20–40	35–106	82–181
2015	17–26	18–38	33–105	75–180

Note: Prices are applicable for fiber tows having a filament count of 12,000 and 24,000. Prices shown represent average prices for continuing customers. Standard-modulus fibers have a modulus of 33–37 million psi; intermediate modulus is 40–45 million psi; and high modulus is 50–60 million psi. [38]

Small tows[n] find applications in the more demanding aerospace market and in some industrial applications, such as pressure vessels, offshore risers, transportation, and stressed components. Large tows are mainly used in automotive, wind, and construction applications. Competition between the two groups of producers occurs in 12K- and 24K-filament-per-tow products for sporting and industrial goods, where mechanical requirements are lower. [38]

Exhibit 4-8 indicates a more recent estimate of end-user[o] carbon fiber prices based on a high-level categorization by fiber grade only.

Exhibit 4-8. Price of carbon fiber, by grade

Grade	End-user Price Range (USD/kg)
Aerospace	66-176
Automotive (racing and high-end sports cars)	18-33
Industrial, sporting goods, wind energy, etc.	22-44

Data source: MarketsandMarkets [31]

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[n] Small tow refers to <12K filaments per tow.

[o] End-user prices are typically higher than import/export and seller's prices due to factors like smaller purchase quantities, profit margins and some other charges.

4.1.4 Recycled Carbon Fiber

Recycled carbon fiber can retain at least 90 percent of the tensile strength of virgin fiber with no change in modulus and a 50 percent lower cost. Because of these reasons, recycled carbon fiber can be used to fill the supply gap in the virgin fiber market. A 2015 study determined that total GHG emissions for virgin carbon fiber are 29.45 metric tons CO_2 per metric ton of carbon fiber, compared to 4.65 metric tons CO_2 per metric ton of recycled carbon fiber production. [39] Big corporations have taken initiative to recycle and reuse their carbon fiber waste. Airbus has set a target of recycling 95 percent carbon fiber waste by 2025 and BMW is determined to recycle carbon fiber scrap from its i-series vehicles.

Until 2025, the global carbon fiber market is projected to be dominated by virgin fiber in terms of value and volume. However, due to lower GHG emissions and costs, recycled fiber is projected to grow at a faster pace compared to virgin fiber.

4.1.5 Opportunities and Drivers

Aerospace giants like Boeing, Airbus, Embraer, and Bombardier are undertaking manufacturing consolidation projects for new single-aisle (narrow bodied) aircrafts. Such aircrafts are projected to command around 70 percent share of future commercial aircraft demand; these aircrafts will drive new demand for carbon fiber in 2020–2025.

Carbon fiber's high strength-to-weight ratio drives recent adoption to make lightweight vehicles; this property is key to CO_2 emission reduction discussions in the automotive sector. New technologies and agreements are projected to be a boon to the carbon fiber market. A plasma oxidation process developed jointly by Oak Ridge National Laboratory and 4M (an RMX subsidiary) would reduce energy consumption by 75 percent and may be used to produce all grades for carbon fiber. Daikin University has also entered into agreements with LeMond Composites and Australian Future Fiber Research and Innovation Center to produce low-cost, low-energy carbon fiber. Other technological drivers include automated composites production line (commissioned by HRC, China), an Industry 4.0 smart factory (Changzhou, China), and thermoplastic composites.

Due to the high stiffness offered by carbon, carbon fiber-based composites are used in manufacturing large wind turbine blade components. Europe is the largest user of carbon fiber in wind energy. Emerging economies like China, Brazil, and Indonesia are also driving carbon fiber demand by increasing reliance on renewable wind energy.

Innovation in product offerings like mining truck trays, geopolymer cement, and corrosive chemical tank containers, which are lightweight, durable, and non-corrosive, is driving carbon fiber demand. Moreover, the carbon fiber composites-based medical equipment market for items like imaging components, prosthetics, wheelchairs, surgical tables, and oncology treatment, has been growing significantly. Use of continuous carbon fibers in 3D printing in aerospace, automotive, and dental is also on the rise.

Carbon fiber industry (primarily composites) has been expanding beyond traditional markets (North America, Europe, Japan) owing to rapid industrialization and subsequent infrastructure growth of the emerging economies (APAC). The carbon fiber market in the Middle East and African regions is also expected to grow.

4.1.6 Barriers to Entry and Growth

The high cost of carbon fiber is the major factor restraining growth and adoption in large-scale applications. Oak Ridge Natural Laboratory is working to define low-cost carbon fiber technologies. Exhibit 4-8 summarizes price ranges for different grades of carbon fiber. If the price for automotive grade carbon fiber reduces to USD 11–15/kilogram (kg), it may be used on a much larger scale.

4.2 SYNTHETIC GRAPHITE

Synthetic graphite is an expensive, high-purity alternative of graphite used in high-end applications like electric-arc furnaces (steel manufacturing) and battery electrodes. It is also used as a polymer additive, a flame retardant, and in semi-conductors. Almost all its products find applications in the automotive, electronics, and steel-manufacturing sectors of the fast-growing APAC economies; because of this, these countries (primarily China) either already do or are expected to hold a significant share of the synthetic graphite market. Unless otherwise stated, the source of all information in this section is from MarketsandMarkets's *Synthetic Graphite Market: Growth Analysis & Forecast till 2025*. [40]

This section describes its share in the overall graphite market,[p] its market segmentation by application and region, leading producers around the world, and active areas of innovation in the market. End-user prices for the global synthetic graphite (syn-graphite) market are also presented. Finally, there is a note on drivers and barriers to market growth.

4.2.1 Market Overview

The graphite market is highly fragmented with several domestic players serving local markets. Since syn-graphite is a type of graphite, some of the market-information is available for the broader category of graphite. However, the granularity of information is clearly indicated throughout this section.

4.2.1.1 End-Use Applications

Graphite finds applications in a broad array of products like anti-corrosive paints, industrial lubricants, and polymers, and tools like mechanical seals and brake-linings. Based on the global graphite market, these applications are categorized into refractory,[q] foundry,[r] battery, friction product, lubricant, and others (including recarburizing[s] and making of carbon brushes, etc.). Exhibit 4-9 shows synthetic graphite market segmentation by application.

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[p] The overall graphite market is segmented by type into natural and synthetic graphite.

[q] Refractories are ceramic materials designed to withstand temperatures more than 1000°F.

[r] A foundry is a factory that produces metal castings.

[s] Carburization is a process of making steel more carbon intensive.

Exhibit 4-9. World: synthetic graphite market by application

Application	Market Size ($MM USD)			Market Size (kiloton)		
	2019	2020	CAGR (2020–2025)	2019	2020	CAGR (2020–2025)
Refractory	8,014.1	7,300.9	5.5%	901.7	814.5	4.3%
Others*	4,823.4	4,378.0	3.6%	420.2	378.2	3.2%
Battery	2,921.3	2,563.1	7.7%	266.6	231.9	7.3%
Foundry	2,027.6	1,881.2	3.2%	248.9	229.0	2.8%
Lubricant	1,423.2	1,291.8	3.7%	176.2	158.5	3.3%
Friction Product	863.6	801.3	3.9%	104.9	96.5	3.5%
Total	20,073.2	18,216.2	5.0%	2,118.4	1,908.6	4.2%

* Like recarburizing and making carbon brushes

Refractory applications—which involve bricks, molds, ladles, and steel making—lead the mix with a projected share of around 40 percent by value and 43 percent by volume, by 2025. Recarburizing and carbon brushes come in second, and batteries come third. Batteries have the highest CAGR at 7.7 percent (7.3 percent) in the 2020–2025 period, by value (volume). In addition to use of batteries in electronics, their use in electric vehicles will also continue to facilitate growth for graphite.

4.2.1.2 Market Size

The graphite market can be divided into natural and synthetic. Natural graphite is mined, varies in crystallinity, is a good conductor of heat and electricity, and is a highly refractory material. It has a higher demand due to its ability to support ferroalloys production. Exhibit 4-10 indicates this segmentation.

Exhibit 4-10. World: graphite market by type

Application	Market Size ($MM USD)			Market Size (kiloton)		
	2019	2020	CAGR (2020–2025)	2019	2020	CAGR (2020–2025)
Natural Graphite	2,040.2	1,844.0	6.4%	1,602.7	1,426.4	5.3%
Synthetic Graphite	20,073.2	18,216.2	5.0%	2,118.4	1,908.6	4.2%
Total	22,113.3	20,060.3	5.1%	3,718.2	3,376.3	4.7%

Among natural graphite subtypes, flake graphite had the highest demand in 2019. Syn-graphite is three to four times more expensive than natural graphite because of superior quality and purity (>99 percent), which can support ferroalloys production. Syn-graphite holds a huge share by value in the overall graphite market (around 91 percent in 2019). However, its share by volume is not as high (57 percent in 2019). Despite the high price associated with syn-graphite, the syn-graphite market is projected to grow at a rate of 4.2 percent in 2020–2025.

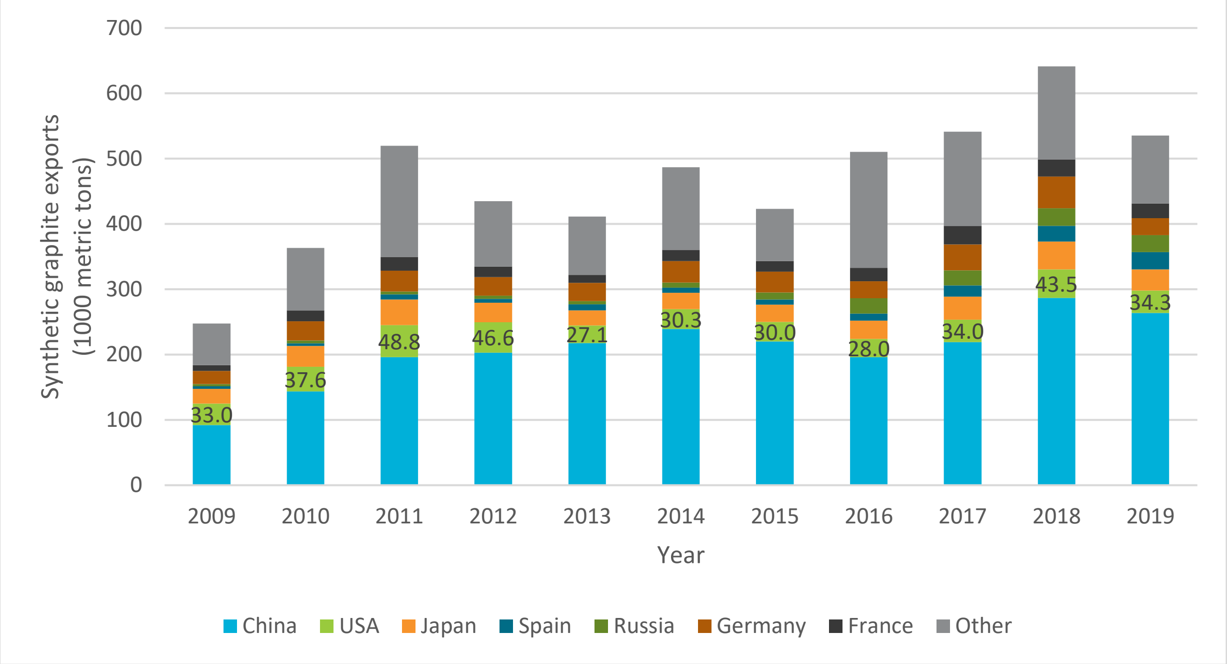
The market value and volume of each of the five regions, namely, APAC, North America, Europe, Middle East and Africa, and South America, are indicated in Exhibit 4-11.

Exhibit 4-11. World: synthetic graphite market by region

Region	**Market Size ($MM USD)**			**Market Size (kiloton)**		
	2019	**2020**	**CAGR (2020–2025)**	**2019**	**2020**	**CAGR (2020–2025)**
APAC	11,788.4	10,813,3	5.3%	1,299.4	1,182.5	4.5%
Europe	3,064.9	2,718.7	3.8%	289.6	254.8	3.0%
North America	2,724.0	2,438.3	4.8%	270.2	240.0	4.0%
South America	1,808.1	1,622.1	4.9%	188.8	168.0	4.1%
Middle East	687.7	623.9	4.0%	70.3	63.3	3.2%
Total	20,073.2	18,216.2	5.0%	2,118.4	1,908.6	4.2%

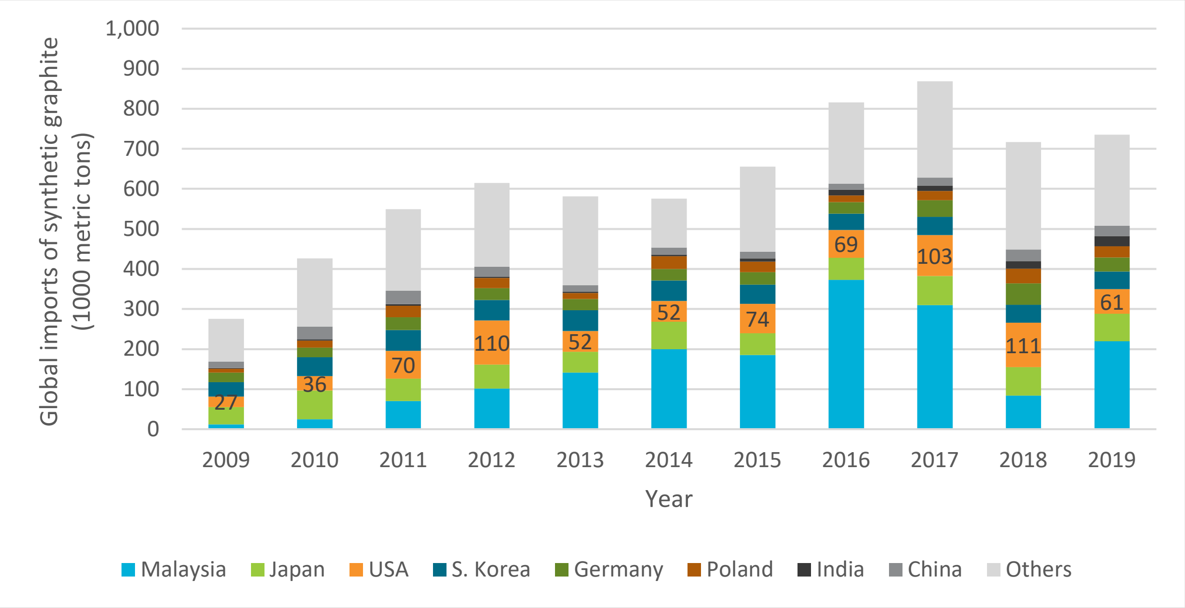
China dominates exports in all categories except colloidal graphite. Chinese exports of artificial graphite grew every year between 2009 (following the global economic downturn) and 2014 at 21.1 percent CAGR. They declined in 2015 and 2016 before increasing again by 12 percent in 2017 and 31 percent in 2018, then falling by 8 percent in 2019. Overall, Chinese exports of artificial graphite grew by an average of 11 percent CAGR during 2009–2019 compared to a global figure of 8 percent CAGR. A timeline of global exports can be observed in Exhibit 4-12. The United States has maintained a steady stream of exports from during 2009–2019 with 2019 ending with 34,300 metric tons of export. [41]

Exhibit 4-12. Global exports of synthetic graphite by country, 2009–2019 (1000 metric tons); U.S. exported 34,300 metric tons in 2019



Imports of artificial graphite products by the main country of destination are shown in Exhibit 4-13. Japan and the USA were, historically (prior to the 2010s), the largest importers of artificial graphite. US imports can be the largest of any country at over 100,000 t/yr (2012 and 2018) but show marked volatility and be around half that in some years.

Exhibit 4-13. Global imports of synthetic graphite by country, 2009-2019 (1000 metric tons); U.S. exported 61,000 metric tons in 2019



APAC leads in market value (59 percent share in 2019) and volume (61 percent share in 2019) by a big margin, primarily due to rising demand for graphite composites in automotive manufacturing. It also has the highest CAGR in the projection period. Europe and North America are the next two contenders; they both have a very similar projected market share in 2025 but North America is going to see a growth rate higher than Europe by 1 percentage point.

Within North America, the United States has the biggest synthetic graphite market share by value at 77 percent in 2019. Among the sub-types, the United States sees a much higher demand for higher-quality syn-graphite than the natural alternative. From application standpoint, refractories, recarburization and carbon brush production, and batteries use the most syn-graphite. The batteries segment has a CAGR of 8.7 percent (the average across applications is 5.0 percent).

4.2.1.3 Leading Producers

Many of the leading producers offer an array of other carbon products like carbon black, lubricants, carbon-fabrics, and carbon fibers, along with natural/syn-graphite. Exhibit 4-14 lists some of the producers of graphite-based products and their key applications. SGL Group, which was a key producer of carbon fiber is also among the top producers of graphite products.

Exhibit 4-14. Leading producers of graphite-based products

Producer Name	Headquarters	Graphite Products Offered	Key Applications of Products Offered
Graftech International Ltd.	Ohio, United States	Electrodes, advanced graphite, thermal management graphite, powders, expandable flakes, gaskets	Steel production, aerospace-defense, lighting and electronics, metallurgy and polymer additives, insulation, fire retardant additives
Triton Minerals Ltd.	Perth, Australia	Expandable graphite, spherical graphite, graphene oxide, composite graphite-sheet	Gaskets and sealing materials, lithium-ion batteries, solar cells and polymer composites, electronic parts, and battery heat shields
Hexagon Resources Ltd.	Brisbane, Australia	Flake graphite, graphene	Refractories, batteries, carbon brushes, flame retardants, electronics, and sporting equipment
Mason Graphite, Inc.	Canada	Graphite, graphene	Refractories, batteries, carbon brushes, flame retardants, electronics, and sporting equipment
Focus Graphite, Inc.	Ontario, Canada	Graphite	Lithium-ion battery anodes
NextSource Materials Inc.	Toronto, Canada	Graphite, graphene	Liners, arc-furnaces, photovoltaic-cells, lithium-ion batteries, electronics
SGL Group	Hessen, Germany	Electrodes, equipment solutions, fine-grain and expanded graphite	Electric-arc furnace, heat exchangers, photovoltaics and semiconductors, automotive and wind energy
Mersen Group	La Defense, France	Anti-corrosion and process equipment, electrical components, advanced materials	Anti-corrosive materials, heat exchangers, carbon brushes, purified and coated graphite parts, refractory parts
Graphite India Ltd.	Kolkata, India	Electrodes, impervious graphite equipment	Steel and other non-ferrous manufacturing, agrochemicals
Heg Ltd.	Noida, India	Electrodes, customized graphite	Steel industries and other client-specified applications
Tokai Carbon Co. Ltd.	Japan	Electrodes	Electric arc furnaces for different steel types
Toyo Tanso Co. Ltd.	Osaka, Japan	Special graphite, graphite sheets	Solar cells, atomic power, semiconductors, gaskets, battery parts

4.2.1.4 Notable Innovations within Market

From the perspective of number of patents filed, innovation in synthetic graphite is lower than that of carbon fiber. Within 2016–2020, a total of 94 patents were published, compared to 9,055 patents related to carbon fiber (in 2018–2020). China accounted for more than 80 percent of this patenting activity with the United States having 7 percent.

The topics for patents in 2019–2020 include many mentions of syn-graphite-hydrochloric acid furnace technology improvements. There are also mentions of products made from syn-graphite like thermally conductive thin and thick films and their unwinding mechanism, negative electrodes for lithium-ion batteries, and energy-saving, friction-improving industrial gear oil.

4.2.2 Pricing Estimate

Average end-user prices[t] of synthetic graphite are available from the MarketsandMarkets report in the range of $9,000–10,500/metric ton across regions. [31] It is seen that APAC has the lowest price due to lower labor and utility costs and abundant availability of materials, whereas Europe has the highest price.

A projected supply-demand gap may alter the price in the next five years. Moreover, a changing array of applications and capacity expansions introduce regular fluctuations in the prices.

4.2.3 Opportunities and Drivers

Increasing use of storage batteries in consumer electronics and electric vehicles will positively impact demand for lithium-ion batteries and fuel cells in the coming years. The electrodes for such cells/batteries use flake and syn-graphite, thereby, driving their demand. Ongoing developments in the electric vehicles segment alone signals a demand more than 2019 global production, by the next decade.

Like carbon fiber, demand for graphite in the wind industry is witnessing growth; this is due to its properties, like high stiffness and light weight, that are useful in turbine blade construction.

Graphite demand is also driven by its increasing use in lightweight, fuel-efficient structural components in the aerospace industry. More recent applications include airframes, fuselage, and rotor blades. Moreover, availability of different grades of graphite may provide growth opportunities by expanding applications industries like marine, sporting goods, and pipes and tanks.

4.2.4 Barriers to Entry and Growth

A graphite-export duty of 20 percent by China and limited productions in other regions of the world is projected to restrict the supply of graphite, globally. Hence, there is going to be a potential supply deficit in the future.

High cost of producing syn-graphite may also inhibit the growth of the market in the near future as such high-purity, composite product may only be used in high-end applications.

4.3 CARBON NANOTUBES

CNTs are carbon tubes with a diameter on the nanometer scale. Discovered in 1991 [42], the term "carbon nanotube" most often refers to a SWCNT, which comprises a single sheet of graphene rolled into a tube, as demonstrated in Exhibit 4-15. Despite this understanding, more

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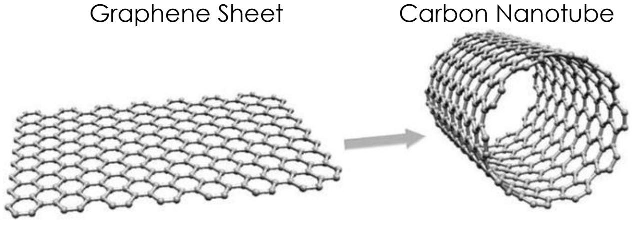
[t] End-user prices are typically higher than import/export and seller's prices due to factors like smaller purchase quantities, profit margins, and other charges.

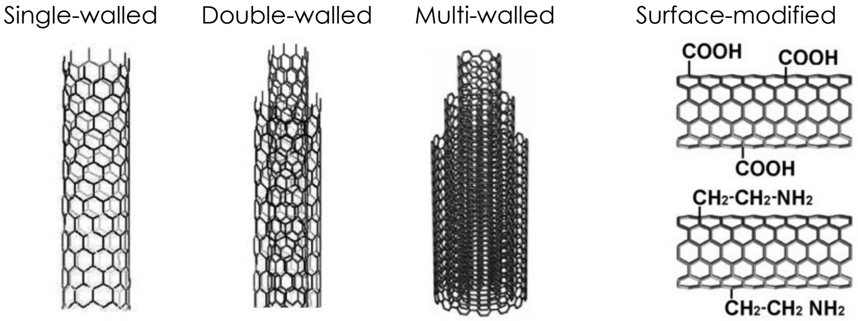
complex nanotube structures can be constructed and have varying functions and purposes: double-walled, multi-walled, and surface-modified nanotubes (Exhibit 4-16).

Exhibit 4-15. Single-wall carbon nanotube



Used with permission from Saleh and Koller [43]

Exhibit 4-16. Types of carbon nanotubes



Used with permission from Jackson et al. [44]

CNTs' nanostructure and strength of the carbon-carbon bonding give it unique and valuable properties. They are known to have a high electrical conductivity [45] or be semiconductors [46], traditionally have a remarkable tensile strength [47], and are powerful thermal conductors [48]. These properties have led to high expectations that CNTs will be a valuable product in electronics, optics, composite materials, nanotechnology, and other future applications within material science.

4.3.1 Market Overview

This section provides an overview of CNT market characteristics, highlighting its end-uses, market size, leading producers, and recent and upcoming notable innovations in the market. Additional analysis has been performed to review the environmental impact of CNT and potential barriers to entry that can be anticipated in the current market.

4.3.1.1 End-Use Applications

The unique properties of CNTs have led to the materials application across numerous applications. Across all applications, the total market is valued at over $1.7 billion in 2020 and is forecasted to have a 15 percent CAGR from 2020 to 2025.

While aerospace and defense is the most valuable CNT market according to 4-17 ($611.4 MM in 2020 and $1.3 billion by 2025), the electronics and semiconductors application has the largest consumption by volume of CNTs (926 tons in 2020 and 2,607 tons by 2025). The CNTs used within electronics and semiconductors are being used to build devices like field-effect transistors, diodes (like p-n junction diodes), and computer chips. All these devices take advantage of the nanotubes’ high electrical and thermal conductivity. With the recent surge of growth across the electronics industry, especially in semiconductors, demand for CNTs is expected to continue to grow across the globe. While highly dependent on the growth of the aerospace and defense industry, CNTs have seen an increased focus as a lighter component while still improving structural integrity for the aircrafts and providing protection from lightning. [49]

Exhibit 4-17. CNT global market size by end use industry

Application	Market Size ($MM USD)			Market Size (metric ton)		
	2019	2020	CAGR (2020-2025)	2019	2020	CAGR (2020-2025)
Advanced Materials	249.1	247.0	13.1%	769.1	833.1	21.4%
Electronics & Semiconductors	260.2	259.8	14.5%	848.5	926.0	23.0%
Chemicals & Polymers	230.1	229.6	14.3%	742.9	810.2	22.8%
Batteries & Capacitors	194.8	194.6	14.6%	627.8	685.6	23.2%
Energy	158.7	158.6	14.7%	510.2	557.4	23.2%
Aerospace & Defense	608.1	611.4	16.4%	287.4	315.8	25.0%
Medical applications	58.4	58.4	15.2%	179.8	196.5	23.7%
Others*	18.1	18.1	14.1%	53.5	58.2	22.6%
Total	1,777.5	1,777.4	15.0%	4,019.2	4,382.8	22.9%

*Others include space elevators, cosmetics, fast moving consumer goods, and technical textiles.

4.3.1.2 Market Size

The increased use of CNTs has had different impacts around the world. APAC has the highest market value and produces the most tonnage of CNTs while also maintaining the highest CAGR. This is largely due to China and India, which have the two largest national markets for nanotubes in the world. More relevant to the study, Exhibit 4-18 shows that the North America region is the second largest market in both value and tonnage, while also having the second highest CAGR. [49]

Exhibit 4-18. CNT market size by region

Region	Market Size ($MM USD)			Market Size (metric ton)		
	2019	2020	CAGR (2020–2025)	2019	2020	CAGR (2020–2025)
APAC	729.3	737.3	16.3%	2,020.0	2,223.1	24.2%
North America	473.8	470.3	14.8%	916.2	990.2	22.3%
Europe	442.2	438.9	13.9%	778.0	840.7	21.4%
South America	84.3	82.9	12.3%	192.4	206.0	19.5%
Middle East & Africa	47.8	47.9	12.0%	112.7	122.9	19.4%
Total	1,777.5	1,777.4	15.0%	4,019.2	4,382.8	22.9%

As shown in Exhibit 4-19, the United States has the largest market share in North America and has one of the largest nanotube markets in the world. The growing market is attributable in part from the development of synthesis methods, the advancement of nanotube technology to enhance their unique properties, and the broadening application opportunities across industries. Similar to the global trends, the aerospace and defense industry has the highest growth rate within the United States (Exhibit 4-20). This growth is largely due to the production of advanced aircrafts within the United States like the Boeing 787, Airbus A350, or the Bombardier family of jets, which are using nanotubes within their production. CNTs have also seen an increased usage within the automotive industry, and can be expected to see a continued growth with the market. [49]

Exhibit 4-19. CNT market size for North America

Country	Market Size ($MM USD)			Market Size (metric ton)		
	2019	2020	CAGR (2020–2025)	2019	2020	CAGR (2020–2025)
U.S.	417.1	414.0	14.8%	806.7	871.8	22.3%
Canada	39.3	39.0	14.4%	76.9	83.0	21.9%
Mexico	17.4	17.2	16.2%	32.7	35.4	24.2%
Total	473.8	470.3	14.8%	916.2	990.2	22.3%

Exhibit 4-20. CNT market size by application in the United States

Application	Market Size ($MM USD)			Market Size (metric ton)		
	2019	2020	CAGR (2020-2025)	2019	2020	CAGR (2020-2025)
Advanced Materials	58.0	57.1	13.1%	162.9	175.4	21.8%
Electronics & Semiconductors	57.3	56.8	14.2%	160.2	173.3	22.4%
Chemicals & Polymers	51.4	50.8	13.4%	142.5	153.7	21.6%
Batteries & Capacitors	44.3	43.9	14.1%	122.4	132.4	22.3%

Application	Market Size ($MM USD)			Market Size (metric ton)		
	2019	2020	CAGR (2020-2025)	2019	2020	CAGR (2020-2025)
Energy	35.9	35.6	14.2%	99.0	107.2	22.5%
Aerospace & Defense	148.4	148.2	16.2%	60.6	66.0	24.6%
Medical applications	17.0	17.0	14.5%	47.4	51.3	22.7%
Others*	4.7	4.6	13.6%	11.6	12.5	21.8%
Total	1,777.5	1,777.4	14.8%	806.7	871.8	22.3%

*Others include space elevators, cosmetics, fast-moving consumer goods, and technical textiles.

4.3.1.3 Leading Producers

While there are some companies whose primary operation is the production of CNTs, most of the production landscape is composed of specialty chemical companies. While specific financial data regarding the performance of the nanotube divisions of companies are not presently available, new product launches and investments that have been made publicly available are able to use as references.

In March 2021, Cabot Corporation announced the launch of a new series of CNTs called ENERMAX 6, which will be the company's latest development in CNTs. The new ENERMAX 6 will be the most conductive multi-walled nanotube product in the company's portfolio. The key benefits of the latest product will include lowering direct current internal resistance of the cell battery, reducing the total loading of conductive carbon additives without a significant loss of electrode conductivity, and increasing aspect ratio. [50]

In May 2015, Belgian company Nanocyl launched a new product Elastocyl™ HTV1001, a product range of MWCNTs elastomeric dispersions. The product is intended for use in applications that require high performance, and provides full compatibility, high- anti-static performance, and has a high tinting power. [51]

In 2017, LG Chem established a new production facility in Yeosu, South Korea, for CNTs, spending $21.5 MM USD. The plant was finished at the end of 2018 and had an initial production capacity of 400 tons of nanotubes each year. In April 2020, LG Chem announced that they would invest an additional $54 MM USD to expand production at the facility by 1,200 tons. [52]

Company profiles and analyses on companies involved in the production of CNTs can be found in Exhibit 4-21.

Exhibit 4-21. Leading producers of CNTs

Producer Name	Headquarters	Nanotube Products Offered	Key Applications of Products Offered
Cabot Corporation	Massachusetts, United States	Athlos	EMI electronics shielding, aerospace and defense, healthcare, 3D printing, and semiconductors
Carbon Solutions, Inc.	California, United States	Single Wall	Specialty polymers, copolymers, polymer composites, electronic materials, and biological structures
Cheap Tubes, Inc.	Vermont, United States	Single and Multiwall	Industrial, construction, electronics, solar, healthcare, paints, polymers, and epoxies
Cnano Technology LTD.	California, United States	Nanotube Powder Series and Conductive Paste Series	Lithium batteries, lead acid batteries, and ultracapacitors
Nanocyl SA	Sambreville, Belgium	Single Wall, Dual Wall, and Multiwall	Transportation, electronics, energy, aerospace, and lithium-ion batteries
Arry International Group Limited	Hong Kong, China	Single Wall, Dual Wall, and Multiwall	Electronical nano components, field emission, multi-functional composites, hydrogen storage, rechargeable lithium batteries, supercapacitors, and biosensors
Arkema SA	Colombes, France	Multiwall	Automotive
Showa Denko K.K.	Tokyo, Japan	Multiwall	Lithium-ion secondary batteries, capacitors, and fuel cells
Toray International Group Limited	Tokyo, Japan	Dual Wall	Electronics
CNT Co., LTD.	South Korea	Multiwall	Batteries, cable, cement, paints, tire, conductive plastics, and automobile interior material
Hanwha Corporation	Seoul, South Korea	Single and Multiwall	Electronics, industrial, energy, packaging, plastics, and glass
LG Chem	Seoul, South Korea	CNTs	Conductive plastics, conductive silicone, lithium-ion battery, and flexible heating sheet or heat-radiating element

4.3.1.4 Notable Innovations within Market

In 2020, 30 patents were filed by companies around the world for new technologies concerning CNTs. One company of note producing innovating technology is C2CNT. Having recently been a finalist in the Carbon XPrize competition [53], the company created a process to create CNTs from CO_2. The C2CNT's proprietary process creates nanotubes via a high-yield electrolysis of the CO_2 in molten salts. The price of their nanotubes is an order of magnitude lower than the current market, and can be retrofitted onto industrial power plants. [54]

4.3.2 Pricing Estimate

The broad use of applications for nanotubes, as well as the range in purity and composition, have created a wide range of end-user prices in the market. Certain SWCNTs with a high purity can cost approximately $500 per gram, making the product significantly more expensive than other competitive products. However, the average pricing distribution shows that the end-user price for CNTs is much closer to $500/kg. The disparity of the average pricing compared to the $500 per gram product is because the majority of industry demands for nanotubes do not require the high level of purity that would drive $500 per gram cost. As additional innovations within the CNT market are discovered, the end-user price is expected to be altered with the increased demand for nanotubes. [49]

4.3.3 Opportunities and Drivers

The CNT market is growing fastest in the APAC region, largely because of the significant demand from developing countries. China is the second-largest consumer in the world of nanotubes—fueled by increased growth of manufacturing plants for automotive, aerospace, and wind turbines, as well as the growth in infrastructure development in the country. [49]

Electronics and semiconductors are projected to be one of the most promising growing opportunities for CNTs over the next five years. The electronics and semiconductors sector is already one of the largest consumers of nanotubes and will continue to see significant growth with the increased production of consumer electronics. Nanotubes' unique properties of ballistic electronic conduction and insensitivity to electro-migration, as well as its low thermal expansion coefficient and tenacity, make the product an ideal candidate to be used in products, and will continue to have a growth that reflects the sector's continued projected growth. [49]

The lightweight properties that CNTs share with carbon fiber have created new interest to use the product as a lightweight wiring option as well as in advanced reinforcing materials. However, there is still a need to decrease production costs in order to help incentivize wider usage throughout the automotive and aerospace sectors. [49]

4.3.4 Barriers to Entry and Growth

As CNTs are still a relatively new product, there remains unknown information on the potential impact that nanotubes and their production has on human health and the environment. An existing concern with the production of other nanomaterials is the release of nanoparticles and nano-biotechnical byproducts, which are dangerous for human health. Further research is needed to evaluate the health hazards that CNTs might cause. Regulations have been introduced to manufacturers of nanotubes to help mitigate negative environmental impact from production of nano materials; however, additional regulations are expected. [55] To address current and future regulations and to ensure proper production safety, additional production costs are to be expected for a product that is already burdened with high costs.

4.4 CARBON BLACK

Carbon black is pure, or nearly-pure, elemental carbon most typically found in a powder or bead form. The valuable properties of the product include its dispersibility, thermal and electrical conductivity, and high tinting strength. Above all, it is most often utilized as a strong material reinforcing agent. This reinforcing property is the key contributor to why 90 percent of carbon black is used in rubber applications. [56]

Carbon black is produced through two primary processes: thermal black and furnace black. Thermal black is the original process that utilizes natural gas and heavy petroleum as the reactants. The process relies on two furnaces that operate first to preheat the reactants and then decompose the natural gas into carbon black and hydrogen. The carbon black is separated and further purified, and the hydrogen is most typically recycled as an energy source to heat the furnaces. [56]

The furnace black process uses heavy aromatic oils as a feedstock in a continuous process within a single furnace that decomposes the oils to create the carbon black product. The hydrogen gas is often repurposed to be utilized to provide heat, steam, or electric power within the facility. While the two processes have similar yields, thermal black having a 35–60 percent yield and furnace black having a 35–70 percent yield, the thermal black process produces carbon black particles that are too coarse to be utilized within rubber. [57] As furnace black has better control on the size of particles for the carbon black and a higher yield, it is the better option for mass production and is the more common method used in within the industry. [58] This fact proves to be a barrier to entry for any effort to mass produce carbon black from natural gas, requiring the thermal black process, which will struggle to stay competitive from a price perspective as well as providing a product that is suitable for the largest market for carbon black.

4.4.1 Market Overview

The carbon black market was valued at $11.0 billion USD in 2016 and is projected be valued at $13.8 billion by 2021, with a growth rate of 4.6 percent. [59] Carbon black is a more established product that has not seen any significant innovation over recent years, contributing to the smaller growth rate compared to the other high-value carbon products. The global consumption of carbon black was equal to 12.3 MMT in 2016 and has had a growth rate of 3.4 percent through 2021, reaching a global consumption of 14.5 MMT. North America accounts for 14 percent of the consumption of carbon black, with the United States consuming a projected 1.6 MMT in 2021. [60] The size and stability of the carbon black market, both globally and domestically, proves carbon black to be a viable carbon product alternative from natural gas, but the more established market will prove to be a barrier for new entrants.[u]

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[u] The market analysis of carbon black was not the primary focus of this report; however additional information on the carbon black market can be found in *Market Analysis of Carbon Ores for End-Use Products*. [69]

4.5 HYDROGEN

Hydrogen is the most abundant element in the universe. However, since it reacts with other organic compounds easily, hydrogen is rarely found in pure form on Earth. It must be extracted from its compound to use, for example, utilizing the process of pyrosis to decompose natural gas. Hydrogen can be used as a zero-carbon fuel, meaning that hydrogen does not produce GHG emissions as a result of combustion. This zero-carbon characteristic makes hydrogen attractive to replace other fossil fuels, especially for those industries that are difficult to be electrified, such as steel production.

Hydrogen fuel cells or hydrogen-fueled gas turbines, that use water electrolysis, provide grid balancing services just like battery storage. Fuel cells or hydrogen-fueled gas turbines turn electricity into hydrogen to store when renewable energy sources are over-producing and burn hydrogen to produce electricity when renewable energy production is low.

The purpose of this report is to investigate high-value carbon-based products derived from natural gas. However, given the emerging global interest in hydrogen as a fuel source, and the fact that hydrogen is a by-product of the decomposition of natural gas, it is included in the following section. Note that this section only provides a high-level overview of the hydrogen market as compared to previous sections, which give deeper dive to individual carbon commodity. This report uses publicly available data and research assembled across other activities exploring hydrogen to complete this section.

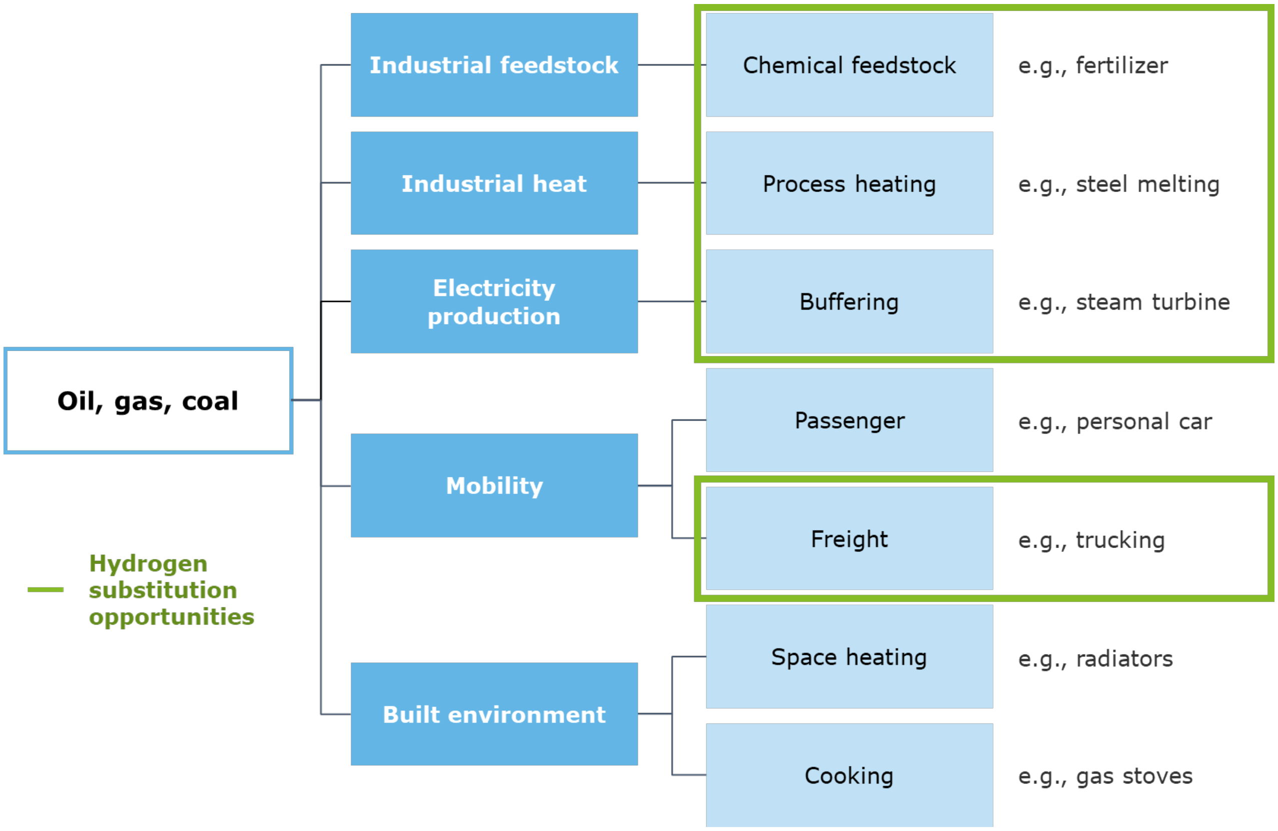
4.5.1 Market Overview

This section provides an overview of hydrogen market characteristics, end-use applications, market size, leading producers, and recent and upcoming notable innovations in the market. Moreover, hydrogen cost to manufacture and environmental impact is reviewed and potential barriers to enter hydrogen market is assessed.

4.5.1.1 End-Use Applications

Hydrogen use for the market today is dominated by the industrial sector. Oil refining and ammonia production have the highest demand for hydrogen. In 2018, the refining industry consumed 52 percent of global hydrogen demand, whereas the ammonia fertilizer industry consumed 43 percent of the global demand. [61] The remaining demand for hydrogen came from methanol and steel production. Aside from the industrial sector, hydrogen also has significant demand potential (to replace traditional fossil fuels) in transportation, building heating, and power generation, as shown in Exhibit 4-22.

Exhibit 4-22. Hydrogen potential to substitute fossil fuel



Note: Data from Deloitte [62]

Hydrogen fuel cell electric vehicles (FCEV) are a viable option to decarbonize the transportation sector. FCEVs have an advantage for faster refueling as compared to battery electric vehicles, making them better for long-range, heavy-duty transportation such as sport utility vehicles, trucks, taxis, and ridesharing vehicles. Off the road, hydrogen can be used to fuel container ships and airplanes. Presently, hydrogen is the only zero-emission fuel alternative for these two transportation applications.

In buildings, hydrogen provides a low carbon emission alternative to natural gas for heat and power. As hydrogen can largely utilize the same infrastructure, hydrogen boilers would be more competitive than heat pumps for older commercial and residential buildings, which require significant refurbishment costs to turn a natural gas heating system into an electric heating system.

In power generation, hydrogen can be blended into natural gas turbines to provide system flexibility and reduce emissions, it can also be used to generate electricity from fuel cells. As mentioned before, combing hydrogen power generation with water electrolysis is one of the leading options for storing excess renewable energy.

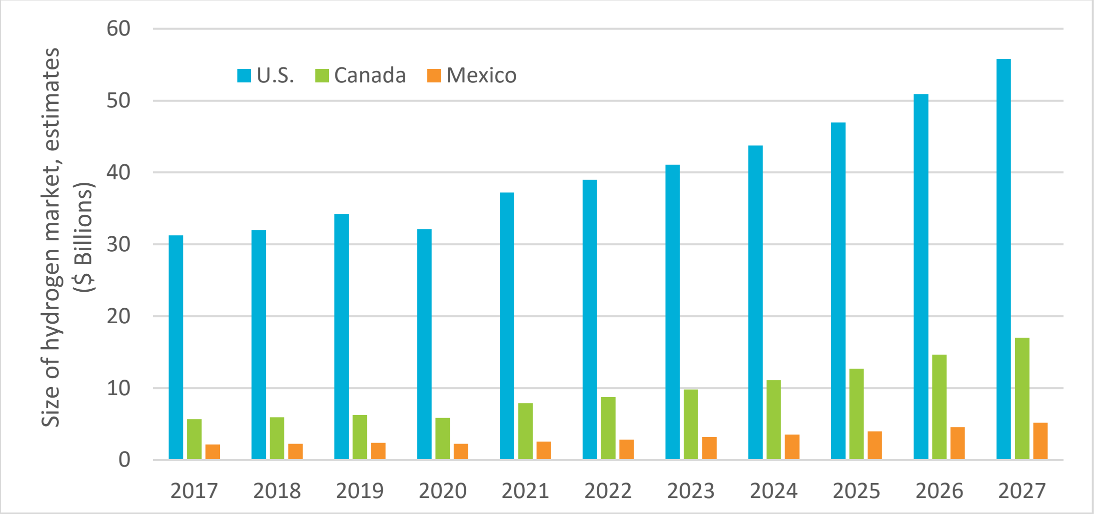
4.5.1.2 Market Size

The global hydrogen market size in 2019 reached $117.49 billion USD. [63] The global hydrogen market is predicted to grow with a 4.32 percent CAGR from 2020 to 2027.

For regional markets, APAC was leading the market in 2019 in terms of revenue as they hold a 32 percent share of the hydrogen market. [63] China is the leading hydrogen producer in the world, producing 22 million tons of hydrogen per year, mostly from dedicated oil- or coal-based plants in chemical facilities or refineries. [64]

Exhibit 4-23 shows the hydrogen market size growth forecast from 2017 to 2027 according to Global Market Insight. [65] In the United States, the hydrogen market was estimated to be $34.24 billion USD in 2019, which is around 30 percent of the world hydrogen market size. The forecasted CAGR for the U.S. market is around 7 percent, much higher than the global CAGR of 4.32 percent.

Exhibit 4-23. Hydrogen market size in North America



4.5.1.2.1 Leading Producers

Three examples of leading producers (grey and blue) for hydrogen include Air Products & Chemicals, Air Liquide, and Linde. While specific financial data regarding the performance of hydrogen production facilities is not presently available, new project launches and investments have been made publicly available.

Air Products is the largest producer and supplier of merchant hydrogen. It offers liquid hydrogen and compressed hydrogen gas in various modes of supply and purities around the world. In July 2020, Air Products signed a 5 billion USD agreement to build a green hydrogen-based ammonia plant in Saudi Arabia. In the United States, Air Products has built more than 20 hydrogen plants in the Gulf of Mexico, including the world’s largest hydrogen pipeline network, which can supply refinery and petrochemical industries in Louisiana and Texas with more than 1 BCF of hydrogen per day.

Air Liquide provides innovative gas solutions using continuously enhanced technologies for the industrial and healthcare markets. It has been developing unique expertise throughout the entire hydrogen value chain, including production, storage, and distribution. In 2021, Air Liquide signed on to participate in a joint project supporting the hydrogen mobility market in Japan. They also penned a deal with H2V Normandy to build a large-scale electrolyzer complex to produce green hydrogen in France.

Linde is a leading global industrial gases and engineering company that covers every link in the hydrogen value chain. The company owns more than 80 hydrogen electrolysis plants worldwide. In 2021, Linde announced it would provide liquid hydrogen and associated infrastructure to the MF Hydra ferry to transport both passengers and cars from its new 24 MW electrolyzer in Germany.

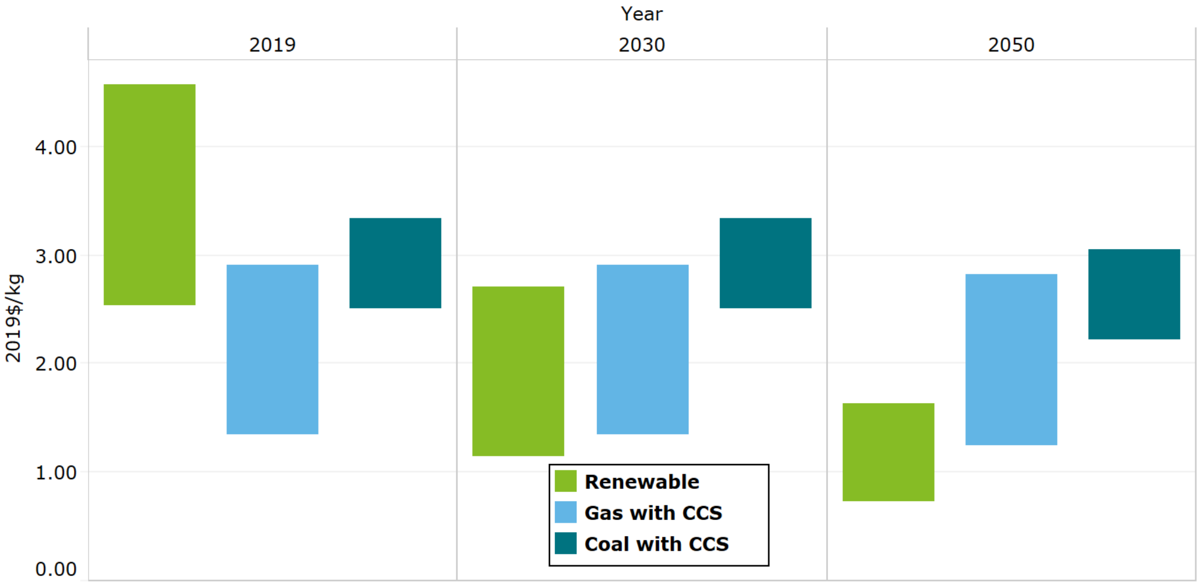
4.5.2 Production Cost for Hydrogen

Hydrogen can be produced from natural gas, oil, coal, biomass, or electricity. In the United States, most hydrogen produced today is from SMR, where natural gas or oil reacts with steam under high pressure conditions in the presence of a catalyst to produce hydrogen. If the hydrogen is produced from SMR without carbon capture and storage (CCS) or from coal/biomass gasification without CCS, a large amount of CO_2 will also be generated; thus, it is called grey hydrogen. If the hydrogen is produced with CCS, it is categorized as blue hydrogen. Green hydrogen is hydrogen produced with water electrolysis where the electricity used to power the process preferably sourced from renewable energy, given the significant energy requirements to power this process. Teal hydrogen is produced through the pyrolysis process, where only a small amount of CO_2 (lower than blue hydrogen) is produced during the process.

This color scale for hydrogen from different production methods indicates the amount of associated GHG emissions. Grey hydrogen production is associated with the most GHG, followed by blue hydrogen, teal hydrogen, and green hydrogen, which produces no GHG through its hydrogen production process.

The price for hydrogen from different production methods can vary significantly by region. This is due to the cost difference across feedstocks regionally, like natural gas and its associated energy cost. Ongoing hydrogen research and development including government funding and policy support are set to influence the cost of hydrogen in the future. Green hydrogen and blue hydrogen are not cost competitive with grey hydrogen today. However, with the growing utilization of water electrolysis, increasing renewables feeding into the electric grid, and more carbon capture utilization and storage development, production costs for green and blue hydrogen, affecting the market price, are likely to reduce drastically over time. The global cost range forecast for blue and green hydrogen production is shown in Exhibit 4-24 (with data from BloombergNEF Hydrogen Economy Outlook 2020 [62]). Note that the production cost of green hydrogen starts to be competitive in 2030 with blue hydrogen and will be \$0.73–1.64/kg of hydrogen in 2050.

Exhibit 4-24. Hydrogen production cost forecast



4.5.3 Environmental Impact

As shown in Exhibit 4-22, the use of hydrogen can reduce GHG emissions since it replaces fossil fuels, thus, reducing the environmental impacts of GHGs. Specifically, hydrogen provides a unique solution for decarbonization for steel production and heavy-duty transportation. Hydrogen has an advantage in the high-temperature process steel industry to replace coke since the process is difficult to fully electrify. In the transportation sector, FCEVs have the advantage of faster fueling, longer range, and greater payload, making FCEVs a superior choice to battery electric vehicles.

Hydrogen technology can also support balancing the grid affected by high renewable penetration, making the grid more reliable and, thus, reducing the environmental impact of GHGs. Intermountain Power Agency and Los Angeles Department of Water and Power (LADWP) announced a project to turn two natural gas generation turbines into hydrogen-fueled turbines in Delta, Utah. The 840 MW plant will serve the existing Intermountain Power Agency customer and demand from LADWP via a high voltage direct-current transmission line. Hydrogen will be produced through water electrolysis and stored in an underground salt dome at the site. This hydrogen system serves as a “battery” concept that works well with the high renewable penetration experienced by LAWPD. The high voltage direct-current line can transfer excessive renewable power from LAWPD for electrolysis to produce and store hydrogen in the underground salt dome. When the renewable energy sources are underperforming, the hydrogen turbines will burn hydrogen to generate power to meet the demand of LADWP. Compared to battery technology, this hydrogen system can charge (store) and discharge (provide) electricity in large quantities for longer periods.

4.5.4 Barriers to Entry and Growth

The major barrier for hydrogen is its high cost as compared to natural gas and other fossil fuels utilized today. Given the sustained low cost of natural gas [66], it is difficult for hydrogen to be cost competitive in various applications such as power generation and building heating. Another barrier for hydrogen is its inherent property of low energy density. One DOE study shows that with the current lowest hydrogen production cost via coal gasification at $1.34/kg, the equivalent natural gas cost is at $10.40 per MM British thermal units (also equivalent to $63.38/barrel oil or $1.36/gallon gasoline), which is much higher than Henry Hub natural gas price (2020 average at $2.30/MM British thermal units). [67] Low energy density makes hydrogen difficult to transport over long distances compared to other types of fuel or even electricity and, thus, less cost effective to transport.

The major barrier for FCEVs aside from the high hydrogen cost is the limited infrastructure such as hydrogen fuel stations. For water electrolysis green hydrogen development, there is not enough renewable energy in the resource mix, which lowers the benefits from green hydrogen given the high energy demands required to power water electrolysis. Within existing hydrogen applications like ammonia production and refining, replacing demand from grey hydrogen to green or blue hydrogen is challenging due to the current cost of hydrogen.

5 EMPLOYMENT IMPACT

5.1 POTENTIAL EMPLOYMENT IMPACT

This analysis is done using a manufacturing multiplier, which is updated periodically by the Economic Policy Institute, most recently in 2019. This multiplier uses data from the U.S. Bureau of Labor Statistics, taking into consideration both backward linkages and forward linkages. It assumes that for every $MM of revenue that a given industry generates, there is a quantifiable number of direct manufacturing jobs that are supported in that industry. For each product, the multiplier from the dominant application is used to estimate the impact on jobs.

Exhibit 5-1 shows which industries are used for each product, and their corresponding direct and indirect jobs multipliers.

Exhibit 5-1. Manufacturing multipliers by industry

Product	Dominant Application	Manufacturing Multiplier	Indirect Jobs Multiplier
Carbon Fiber	Aerospace	2.13	7.17
Synthetic Graphite	Refractories	5.31	8.46
CNTs	Aerospace	2.13	7.17
Carbon Black	Rubber Product	3.15	7.76

Backward linkages are those jobs that are filled by suppliers to the industry, while forward linkages are those that are generated by the industries in which employees spend their wages. Both categories make up total indirect jobs, and will be different for each industry and product, depending on several factors, including reliance on suppliers, and wages earned in a given industry. [68] Exhibit 5-2 provides the estimated impact for each carbon product, based on calculations made using the U.S. revenue in 2025, and each industry's unique multiplier numbers.

Exhibit 5-2. Estimated employment impact by carbon product industry

Carbon Product	2019 U.S. Revenue ($MM)	2025 U.S. Revenue (E, $MM)	Market Penetration	Direct Manufacturing Jobs	Total Indirect Jobs	Total U.S. Jobs Supported
Carbon Fiber	1,765	2,515	5	268	901	1,169
			20	1,071	3,606	4,677
			80	4,285	14,423	18,708
Synthetic Graphite	2,724	3,087	5	820	1,306	2,125
			20	3,279	5,223	8,502
			80	13,114	20,893	34,007
CNTs	473.8	937.7	5	100	336	436

Carbon Product	2019 U.S. Revenue ($MM)	2025 U.S. Revenue (E, $MM)	Market Penetration	Direct Manufacturing Jobs	Total Indirect Jobs	Total U.S. Jobs Supported
			20	399	1,345	1,744
			80	1,598	5,379	6,976
Carbon Black	3,096	4,975	5	784	1,930	2,714
			20	3,134	7,722	10,856
			80	12,538	30,886	43,424
TOTAL	8,059	11,515	5	1,971	4,474	6,445
			20	7,884	17,895	25,779
			80	31,534	71,581	103,115

The intent of this analysis is to determine the number of jobs that would potentially be supported by revenue from products using natural gas feedstocks. Three different penetration scenarios assume that natural gas-derived products will make up 5, 20, or 80 percent of the market share by 2025. Certain assumptions are made in the derivation of the multipliers as well. For example, industries that have a high-level output support fewer jobs per $1MM of revenue, because fewer workers are required to produce that amount of product. Many durable goods such as these products fall into this category. However, the indirect forward and backward linkage jobs for these industries are strong, so they have larger ripple effects throughout the economy. These industries rely on suppliers and raw materials, which support jobs in those areas, and the manufacturers get comparatively high wages, enabling them to spend money to support restaurants, retail, and other indirect jobs. [68]

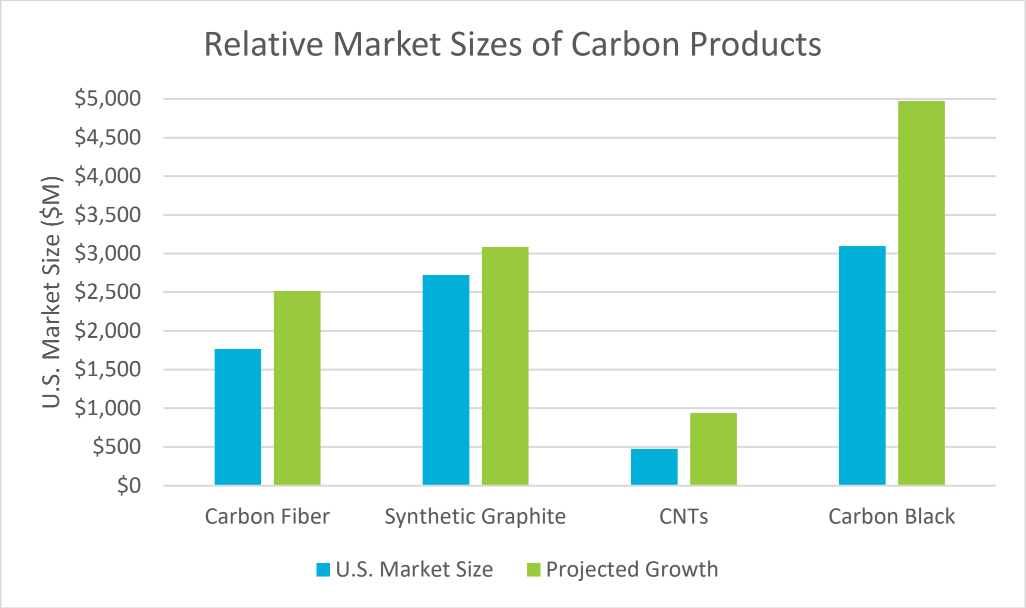
6 CONCLUSIONS

The current rate of venting and flaring of natural gas in the United States presents a unique opportunity to take advantage of a widely available, commonly stranded raw material, and transform it into high-value products that are critical to growing markets. Because there is no additional cost associated with the production of vented/flared natural gas as it is produced as a by-product of oil on a wellsite, the cost associated with this effort would fall primarily on developing and scaling the infrastructure needed to capture and utilize the supply (e.g., small modular devices on the wellsite that can facilitate decomposition to transform natural gas into solid-carbon products).

Emissions from associated gas flaring comprised 0.53 percent of all energy-related emissions in the United States in 2019. Given that only a fraction of total flared volume may be used for producing analyzed carbon products (given the global market size for these products), the benefit to the environment based on carbon emissions reduction may be negligible. However, there are other benefits to the United States in terms of jobs supported, and the possibility of a competitive edge in growing markets.

The carbon products analyzed in this report have large and growing markets, both domestically and globally. These products are also largely differentiated products, meaning that innovative new entrants could capture some of the existing demand given that they have enough capital for initial investment. The relative size of these markets, as well as their projected growth by 2025 is shown in Exhibit 6-1.

Exhibit 6-1. Domestic market size for selected carbon products



The initial capital investment for any of these products is going to be substantial. Although carbon black has a large market, it is fairly mature and is dominated by major players with longstanding customer relationships. Emerging markets with growing applications may have more impact for natural gas utilization. Focusing on the development of modular devices necessary to capture and transform natural gas at the well site will be integral to the success of any of these products. The specific design and function of these devices will vary depending on the product being manufactured, but they will have shared components. Building this infrastructure at well sites is a necessary first step toward capturing the value of vented and flared natural gas resources.

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APPENDIX A: ENVIRONMENTAL IMPACT CALCULATIONS

Flared/vented gas volume in 2019 = 538,479 mcf [15]

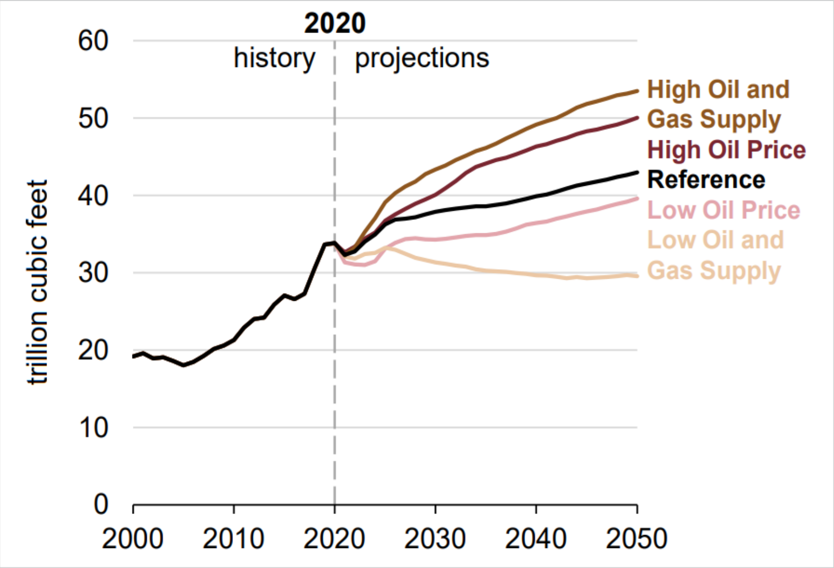
Volume of gas extracted from oil wells in 2019 = 4,626,343 mcf [15]

(Vented/flared volume) / (volume of gas from oil wells) = 11.64 percent

With more awareness and initiatives to reduce flaring, it may make up a smaller fraction of the gas extracted from oil wells. Range of vented/flared fraction in 2050: [5 percent, 11.64 percent]

Dry gas projected volume in 2050: 43 trillion cubic feet (reference scenario of *Annual Energy Outlook 2021* [14], shown in Exhibit A-1)

Exhibit A-1. U.S. dry natural gas production until 2050



Source: EIA Annual Energy Outlook 2021 [14]

15 percent of this dry gas comes from oil formations and is projected to stay steady by 2050 (indicated in *Annual Energy Outlook 2020* [16])

Projected gas production from oil wells in 2050 = 15 percent x 43 TCF = 6.45 TCF

Projected flaring volume in 2050 = [5% x 6.45, 11.64% x 6.45]

= [323, 751] BCF natural gas

Converting to emissions = [17.14, 39.86] MMT CO_2

APPENDIX B: MATERIAL BALANCE SUPPLEMENTAL INFORMATION

Exhibit B-1. Reservoir natural gas composition

	Bakken	Permian	Eagle Ford	Other
Total Annual Flared (BCF)	82.6	91.9	80.5	139.5
Total Annual Flared (BM^3)	9.4	10.1	9.1	13.4
Moles	6.0	6.5	5.8	8.9
CH_4 (mol%)	52.7%	69.3%	64.0%	63.2%
C_2H_6 (mol%)	24.6%	11.0%	16.3%	16.6%
C_3H_8 (mol%)	12.9%	4.7%	8.5%	8.2%
C_4H_{10} (mol%)	1.3%	2.0%	6.5%	2.2%
H_2S (mol%)	3.8%	0.4%	0.0%	1.6%
CO_2 (mol%)	2.8%	1.1%	2.0%	1.8%
N_2 (mol%)	0.0%	10.1%	0.3%	5.3%
He (mol%)	0.4%	0.1%	0.0%	0.2%
Other (mol%)	1.5%	1.3%	2.4%	0.9%

$$n = \frac{P * V}{R * T}$$

Equation 4. Ideal gas equation

Exhibit B-2. Ideal gas values

Ideal Gas Law Values	Value
P – Pressure	101,325 Pa
V – Volume	15,234,000,000 m^3
R- Universal Gas Constant	8.314 $\frac{J}{mol*K}$
T - Temperature	1500 Kelvin

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