

# ISSUE BRIEF **04.28.20**

## Measuring the True Cost of Sustainability: A Case Study in a Green Energy Approach

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*This issue brief is a preliminary paper introducing forthcoming research that will be expanded upon in future publications.*

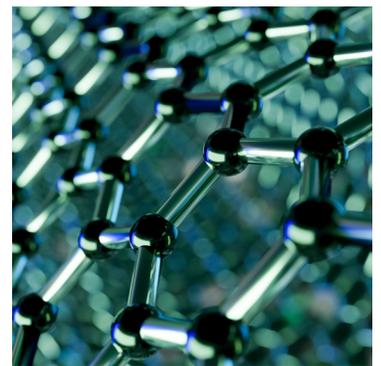
### INTRODUCTION

For nearly two centuries, fossil fuels have powered our insatiable appetites for technological prowess, societal gains, and the possibility of achieving unimaginable new heights. The search for oil and gas has shaped every facet of modern human history and remains a top national priority for many countries. However, this rapid progress has come at a high cost. The accumulated impact from burning fossil fuels has raised concerns over the environmental toll associated with rising anthropogenic carbon dioxide (CO<sub>2</sub>) levels in the atmosphere. We are transitioning to a new age of human development, one where the environmental and societal consequences must now be balanced with economic ambitions. If the fossil fuel industry wishes to remain relevant, it must adapt and explore paths towards zero-carbon or low-carbon energy and carbon utilization strategies.

The U.S. Energy Information Administration (EIA) projects a 28% increase in average world energy consumption between 2015–2040.<sup>1</sup> At the same time, CO<sub>2</sub> emissions must be dramatically reduced to minimize the impact of global climate change. However, a variety of energy outlooks predict that in 2040, fossil fuels will continue to supply 50–80% of total

world energy primary consumption.<sup>2</sup> The transition to low-CO<sub>2</sub> or zero-CO<sub>2</sub> energy technologies is hampered by the fact that there are few suitable alternatives at scale for fossil fuels in the industrial or transportation sectors, which in 2017 accounted for nearly 60% of total energy consumption (representing 44% of global CO<sub>2</sub> emissions).<sup>3</sup> Developing ways of capturing the carbon emissions from fossil fuels and upgrading them to higher-value products may be the most straightforward path towards reducing these emission sources and meeting rising energy demand without resulting in a complete overhaul of these sectors.

There is a growing body of research dedicated to assessing potential pathways towards carbon capture, utilization, and storage (CCUS) from industrial processes.<sup>4</sup> These processes are typically concerned with capturing CO<sub>2</sub> and storing it or converting it into new chemicals. Unconventional processes that eliminate the production of CO<sub>2</sub> entirely, such as the direct conversion of methane in natural gas to hydrogen and value-added carbon materials (otherwise known as methane pyrolysis), have also gained traction among some of the major oil and gas companies. The effectiveness of a given carbon utilization pathway in avoiding or removing carbon from the atmosphere



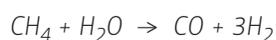
**Nanomaterials have enabled noteworthy progress and technology development, but questions remain around establishing different grades of nanomaterials, routes of exposure during production, use and disposal, nanomaterial characterization, and health and toxicity effects.**

**Adding a life cycle dimension to the business outlook and future legislation will promote technologies and processes that result in more solutions rather than more problems.**

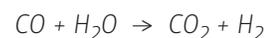
will depend on a variety of factors including the added costs for capturing CO<sub>2</sub> or producing carbon, the relevant timespan in which carbon can be stored, the potential release pathways, the ability to scale these technologies, and policies related to CCUS. Considering these factors, a case study is presented here that considers the technological merits of methane pyrolysis while also addressing real-world implications including health and safety risks and commercial risks for introducing new carbon supply chains.

Hydrogen as a zero-carbon energy carrier has the potential to significantly transform the global energy landscape.<sup>5</sup> Unlike solar and wind energy, hydrogen is a more natural substitute for fossil fuels in sectors that are particularly difficult to decarbonize (i.e. transportation and industrial) and where the ability to quickly respond to sudden increases in energy demand or to maintain consistent energy supply is critical. Hydrogen can be produced from several diverse and geographically dispersed resources, and its utility cuts across multiple sectors including metals refining, fuels upgrading, and ammonia production. Furthermore, hydrogen fuel cells are two to three times more efficient than internal combustion engines, thereby offering additional energy efficiency gains.<sup>6</sup> However, to be competitive with gasoline, the cost of hydrogen production must be lower than \$2/kilogram (kg) (< \$4/kg delivered and dispensed), and this begs the question of how hydrogen production will be scaled to meet future energy demand.<sup>7</sup>

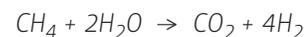
Today, hydrogen demand is predominantly supplied by fossil fuels; approximately 6% of global natural gas and 2% of global coal is used for hydrogen production.<sup>8</sup> In the U.S., 95% of the 10 million metric tons of hydrogen produced annually comes from a process called steam methane reforming (SMR). SMR is a mature technology with a low cost and a high efficiency. In SMR, methane from natural gas is reacted with water to produce hydrogen and carbon monoxide:



The carbon monoxide produced in SMR can undergo an additional water-gas shift (WGS) reaction to produce more hydrogen:

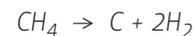


Combining SMR with WGS means that for each molecule of methane, four molecules of hydrogen are produced (1 kg H<sub>2</sub> for every 2 kg CH<sub>4</sub>):



If the reaction is run at its maximum thermodynamic efficiency, this process can produce hydrogen with an energy content of 7 megatons of oil equivalents (MToe) for every 1 MToe expended to run the reaction. If low-cost natural gas from shale production is used to provide methane for SMR, the cost of hydrogen can be reduced to below the \$2/kg target.<sup>9</sup> However, SMR also produces an estimated 9–14 kg of CO<sub>2</sub> for every kg of hydrogen (H<sub>2</sub>), depending on the fuel used to power the process and the overall efficiency. Capturing and storing even a fraction of the CO<sub>2</sub> produced in this process will increase the cost of H<sub>2</sub>, though to what degree will depend on what CCUS technologies are employed. In this light, it may be preferable to explore alternative hydrogen production methods like methane pyrolysis that do not co-produce CO<sub>2</sub>.

Methane pyrolysis involves converting methane to carbon and hydrogen at high temperatures (700–1200°C) and mild pressures (1–5 bar):

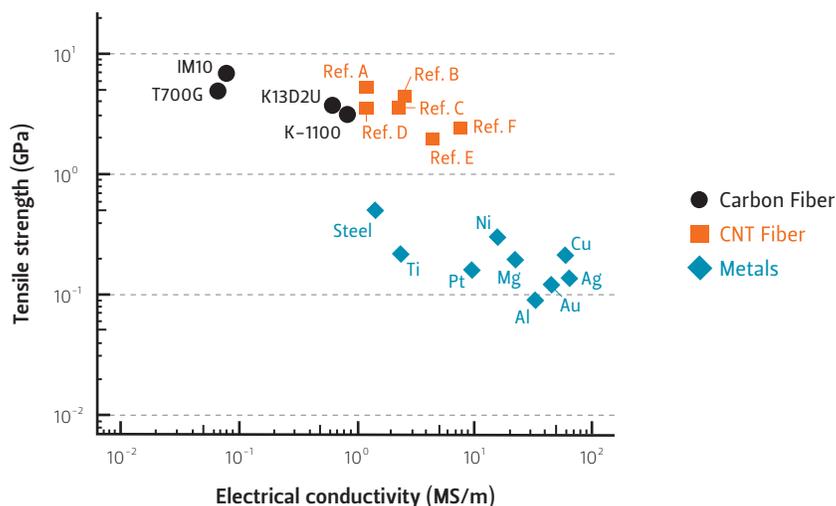


At maximum thermodynamic efficiency, this reaction also produces hydrogen with an energy content of 7 MToe for every 1 MToe expended, but unlike SMR, it does not co-produce CO<sub>2</sub>. Instead, solid carbon is generated which may offer some commercial advantages. The cost of hydrogen production via methane pyrolysis is predicted to be higher than for SMR, but the co-generation and sale of carbon may offset hydrogen production costs, thereby making methane pyrolysis more competitive with SMR. However, the type of carbon that is produced is an important consideration.

At the hydrogen production scales that would be required for a global energy market (~300 MT of hydrogen to meet 10% of 2019 global energy demand), significant carbon production (~1 GT carbon) will be realized.<sup>10</sup> The value proposition of methane pyrolysis relies on the availability of equally large markets that can absorb carbon from a new supply chain.

The largest markets for non-combusted carbon are carbon black (~10s MT), graphite (~0.1 MT), and carbon fiber (~0.1 MT), all of which are only a fraction of the carbon produced that could be expected if hydrogen production was scaled to meet a significant portion of global energy demand. Potential applications for a burgeoning carbon supply chain would need to move beyond the traditional markets. The recent discoveries and research in advanced carbon nanomaterials pose interesting value propositions for carbon supply chains. One such class of carbon nanomaterials, carbon nanotubes (CNTs), has already achieved notable successes since their discovery in 1991. CNTs have stirred a lot of excitement in the research community due to their impressive electrical, thermal, and mechanical properties, and researchers have found potential applications in a variety of fields ranging from water purification to high-strength, lightweight composite materials.<sup>11</sup> As flexible, lightweight, strong conductors, CNTs and CNT-based materials have significant potential. For example, there are promising reports that demonstrate that CNT fibers are approaching electrical conductivities of metals and mechanical strengths of carbon fibers (Figure 1). As shown in Figure 1, CNT fibers have achieved mechanical tensile strengths up to 10 times greater than steel and electrical conductivities up to eight times higher. If the electrical conductivities of CNT fibers are normalized with respect to mass, the best reported CNT fiber has a specific electrical conductivity within 15% of copper, meaning that CNT fibers could substitute metals in cases where saving weight is a top priority. The dual benefit of possessing high strength and high electrical conductivity within a single material makes CNT fibers particularly attractive for electrical wires

**FIGURE 1 — ELECTRICAL CONDUCTIVITIES AND TENSILE STRENGTHS FOR TYPICAL CARBON FIBERS, CNT FIBERS, AND METALS**



**SOURCE** Data compiled by Oliver Dewey and Lauren W. Taylor, Rice University, Department of Chemical and Biomolecular Engineering, 2020.<sup>12</sup>

or coaxial cables where metals like steel, copper, and aluminum are frequently used.

Because of their comparatively low tensile strengths, metal cables are often overengineered, using higher amounts of metals than would necessarily be required in order to prevent cable failure or breakage. With their much higher tensile strengths, CNT fibers will be less likely to fail or break. The market for metal cables (~1 GT per year for steel, aluminum, and copper) is much larger and higher in value and could be more amenable to absorbing new carbon supplies from high-volume hydrogen production. Hydrogen production via methane pyrolysis may be a potential solution to simultaneously meet rising global energy and materials demands while reducing CO<sub>2</sub> emissions. However, the sustainability potential is not yet known and must be considered from a variety of contexts over the entire supply chain.

Ensuring equitable access to cheap, reliable, and sustainable energy is a crucial component for sustainable community development; access to energy helps to lift nations from poverty and powers progress. The adoption of the United Nations (U.N.) Sustainability Development Goals (SDGs) in 2015 by 193 countries signaled a

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global commitment to promote inclusivity, prosperity, resiliency, environmental stewardship, and a mutual responsibility to uphold sustainable practices. Companies are increasingly held accountable for their sustainability risk profiles and their social responsibility by investors, stakeholders, governments, consumers, trades associations, the public, and others. Achieving the ambitious goals set forth by the Paris Agreement and the U.N. SDGs will require climate leadership and coordination among governments to set ambitious policies and to ensure that companies adhere to Science-Based Targets initiatives (SBTis).<sup>13</sup>

Within the context of scaling methane pyrolysis or substituting high-volume metals with carbon, transparency along the entire supply chain is crucial. Companies are being pressured by stakeholders, governments, and the public to adopt a strict set of environmental, social, and governance (ESGs) performance metrics. ESGs promote ethical business practices that do not impose on or harm communities and the environment and do not transgress legal mandates. By proactively incorporating ESGs into their strategic visions and maintaining transparency in their practices, companies avoid or minimize risks to human health and the environment, prevent costly social impacts, and limit negative public perceptions that could impact future growth, stall new product development or current practices, or invite enhanced regulatory scrutiny. Businesses that adopt a standard set of ESGs assure the public and private sectors that sustainability is a priority and reinforce profitability over the long term. The ESG field is still in its infancy, and standardized guidelines that enable ESG assessments to be comparable across companies or countries do not currently exist. Regardless, a prerequisite to measuring ESGs is a comprehensive life cycle analysis of business activities over the entire supply chain.

Life cycle analysis (LCA) is a strategy to methodically account for the social, environmental, and economic impact associated at all stages of business operations, from raw materials sourcing to end-of-life management. A thorough LCA reveals potentially unintended consequences

arising at stages before or after the main business activity and underscores the need to balance economic gains against negative social and environmental impacts. When incorporated early, LCAs guide informed decision-making and investments, highlight opportunities for sustainable new growth, and mitigate long-term risks. LCAs establish a level playing field that enables more direct comparison of net impacts for breakthrough technologies. This is critical for assessing the best strategies in CCUS and sustainable energy technologies and for developing new materials markets. For methane pyrolysis, it is important to quantify the CO<sub>2</sub> abatement that occurs from substituting fossil fuels with hydrogen and to consider how many carbon nanomaterials may be produced and utilized. However, it is also important to consider other factors like methane emissions during the process itself, potential routes for carbon release into the environment downstream, and the time scale over which this all occurs. If this carbon is integrated into carbon nanomaterials, under what conditions does it pose an unreasonable risk to human life and the environment? Nanomaterials have enabled noteworthy progress and technology development, but several challenges remain in assessing nanosafety risks. Questions around establishing different grades of nanomaterials, routes of exposure during production, use and disposal/recycling, nanomaterial characterization, and health and toxicity effects pose potential barriers to widespread adoption.

Additionally, legislation has not kept pace with the rapid rate of innovation. Enacting new environmental and safety laws should address the entire life cycle of the process. For methane pyrolysis, effective legislation will address hydrogen production and utilization in addition to allocating resources towards increasing the understanding and the management of potential risks associated with carbon nanomaterials throughout the supply chain, from production to end-of-life. Equal consideration should be given to changes in the materials sector triggered by substituting industrial materials like steel, aluminum, or copper that feature large carbon footprints with materials that are expected to have a much lower carbon

footprint, like CNTs. A life cycle analysis enveloping the entire supply chain for metals like steel, aluminum, and copper would reveal if emissions from the mining and production of metals can be mitigated by substituting them with carbon nanomaterials. Adding a life cycle dimension to the business outlook and future legislation will promote technologies and processes that result in more solutions rather than more problems.

Scaling methane pyrolysis for hydrogen production will result in significant quantities of carbon. Beyond the technical hurdles of making the process efficient and scalable, expanding on or creating new carbon supply chains from the development of large-scale methane pyrolysis will also require companies to surmount regulatory hurdles. The regulation of industrial and specialty chemicals, including carbon nanomaterials, falls under the Toxic Substance Control Act (TSCA) in the United States and in the Registration, Evaluation, Authorization, and Restriction of Chemicals Regulation (REACH) in the European Union. The TSCA requires the Environmental Protection Agency to undertake a risk analysis of both existing and new chemicals to determine whether a given chemical or chemical composition presents an “unreasonable risk” and should therefore be subject to strict regulation. Under REACH, industries are responsible for proving the production and use of chemicals circulating in the market do not pose an unreasonable environmental or safety hazard and for providing safety information. Both the TSCA and REACH seek to mitigate, minimize, or eliminate risks for current chemicals and new chemicals during production, downstream activities, typical use, and end of life. In developing a new carbon supply chain, companies must be compliant with these regulations or other related regulations (i.e., Occupational Safety and Health Administration standards). There is still debate on the nanotoxicity of carbon nanomaterials as the field grapples with establishing different classes of CNTs and with balancing potential health and safety risks with beneficial new CNT applications.<sup>14</sup> In this effort, companies should strive for transparency and not underestimate public perception, which could derail a project

before it is completed. Equal care should be taken to anticipate and address both technological and regulatory hurdles.

The world needs access to sustainable, reliable, and affordable energy as well as materials necessary for construction, infrastructure, equipment, automobiles, etc. For nearly two centuries, this need was supplied by burning fossil fuels and using steel, aluminum, and copper, for example, which have their own large greenhouse gas footprints. However, we are entering a new age of human development where economic achievement, social responsibility, and environmental stewardship must be balanced, where both governments and companies must work collaboratively and act as climate leaders for change. Promising CCUS technologies and alternative energy solutions have already been scaled, are currently under development, or are being considered to avoid or reduce greenhouse gas emissions in the atmosphere. On the surface, these proposed solutions support U.N. SDGs but unless they also include a thorough LCA, we cannot know for certain if they will be sustainable over the long-term. As new supply chains for carbon and CO<sub>2</sub> are introduced, the impacts for new technologies along the entire supply chain must be considered. Companies will need to weigh the economic costs with the social benefits of mitigating greenhouse gas emissions, determine the effect on the environment from materials sourcing to end-of-life management, and anticipate any potential health and safety risks associated with new materials or new processes. Companies must accurately measure their sustainability progress for their business operations against ESG metrics. Governments and companies must also employ techniques that enable them to accurately compare different technologies and guide investment decisions towards solutions with a net positive effect. Sustainable progress cannot be achieved when health, safety, and environmental risks outweigh emissions reductions. A more sustainable future is possible but only when economic, social, and environmental elements are in harmony.

**Sustainable progress cannot be achieved when health, safety, and environmental risks outweigh emissions reductions.**

## ENDNOTES

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