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The Advanced Carbon Economy: A Sustainable Hydrogen Pathway

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INTRODUCTION

Lowering the carbon footprint of energy use is at the core of discussions on energy transitions and hydrogen has become a part of that dialogue. Decarbonization efforts and commitments from governments and industries are rising[1] due to global climate and sustainability targets, and many are exploring and adapting innovative technologies and business models with the goal of zero-carbon or low-carbon energy and carbon utilization strategies. As the challenges and complexities of the energy transition evolve, industry is also transitioning to a new age of human development, one where the environmental and societal consequences must now be balanced with economic ambitions.

Sustainability is largely understood in three large interconnected spheres: social, environmental, and economic.[2] Identifying pathways to balance each one of these components is complex and has deep and unique connections that demand systems-wide efforts. In 2018, sustainable investments increased 34%, reaching $30 trillion since 2016.[3] This shift aims to focus on profit and economic growth, while considering available resources, the environment, and existing social and economic systems.

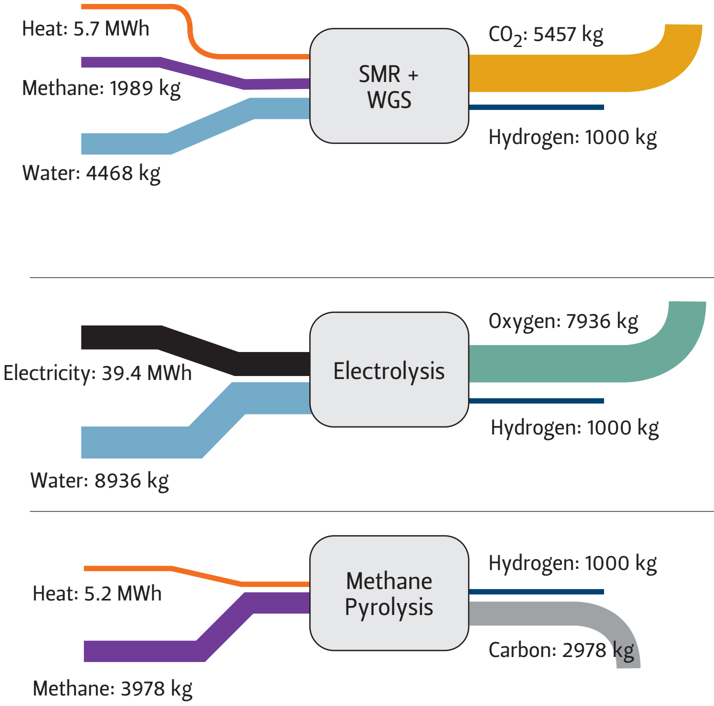
HYDROGEN PATHWAYS

Hydrogen, as a zero-carbon energy carrier that can be stored prior to use, has the potential to significantly transform the global energy landscape.[4] There are multiple technologies that can be deployed to produce hydrogen, and the "hydrogen" is a color-code that differentiates the many existing and emerging production technologies, not all of which have been commercialized. Figure 1 provides a brief summary of the hydrogen spectrum, although it should be noted that this is not a universal characterization. It should also be noted that the use of hydrogen as an energy source has been explored for years, but commercial hurdles have largely been insurmountable and the costs vary across the color-code of hydrogen.

The current market for hydrogen is primarily geared toward the use of hydrogen in refining, fertilizer production, metallic ore reduction, chemical applications, and as liquid fuel for rockets. However, its promise as a fuel to decarbonize energy systems is linked to potential applications across a range of end-use sectors from transportation to electric power to industry, and the ability to produce it while limiting CO_2 emissions. This latter point is important: for hydrogen to be low-carbon, the negative CO_2 externality must be abated, which pushes the production

Methane pyrolysis (turquoise hydrogen) can be a favored technology for any decarbonization strategy in regions with readily available, abundant, and affordable hydrocarbon resources and existing infrastructures with well-developed supply chains to produce zero-emission hydrogen and a competitive solid carbon material.

FIGURE 1 — HYDROGEN PRODUCTION PATHWAYS AND COMPARATIVE CARBON EMISSIONS



GREY/BROWN Production

Uses natural gas or gasified fossil fuel as feedstock through a steam reformer

(SMR) $CH_4 + H_20 \longrightarrow CO + 3H_2$

(WGS) $CO + H_20 \longrightarrow CO2 + H_2$

BLUE Production

Grey/Brown with carbon capture

GREEN/PINK Production

Uses water as a feedstock through an electrolyzer

$2H_20 \longrightarrow 2H_2 + 0_2$

TURQUOISE Production

Uses natural gas or a gasified fossil fuel as feedstock through a pyrolizer

$CH_4 \longrightarrow C + 2H_2$

SOURCES Graphic from GTM, February 2021. Colors with descriptions based on Medlock, *Forum*, May 2021.

technology options away from grey and brown. Fortunately, regardless of the technology deployed, the end result is a hydrogen commodity that can be used in a multitude of applications. Thus, the choice of technology is reduced to finding carbon-reducing pathways that provide sufficient value for long-term commercial viability.

As highlighted in Figure 1, hydrogen can be produced many different ways. "Grey" hydrogen is the dominant production technology deployed today, using natural gas as a feedstock in steam methane reforming, which results in CO_2 emissions. Hence, expansion of the hydrogen market while also reducing carbon emissions will require different technology options. Some of these technologies include hydrocarbons as a feedstock, but only when paired with a carbon removal technology. "Blue" hydrogen is one such option because it leverages existing hydrocarbon supply chains and associated infrastructures for moving the hydrogen, although scaling up hydrogen production will require new facilities and infrastructure. Blue hydrogen employs carbon capture technology alongside steam reformation, which allows it to avoid stranded costs when existing assets are retrofitted with carbon capture technologies. It can also enable low carbon solutions with fewer new fixed costs by extending the life of existing infrastructures, but it may lead to less CO_2 captured. It can also enable low- carbon solutions with fewer new fixed costs by extending the life of existing infrastructures. However, new infrastructure will be needed to transport and store the captured CO_2. The challenge with grey or brown hydrogen is that CCS adds only to costs (capture, transportation, and storage) without creating any new products.

Production technologies that use electrolysis ("green" and "pink") to split water into hydrogen and oxygen bear significant promise as a low-carbon solution because they generate no CO_2 at the point of conversion. Significant emphasis has been placed on green hydrogen, in particular, with a number of proposed projects in various regions around the world, including a large majority in Europe.[6]

"Turquoise" hydrogen, like blue hydrogen, can leverage existing hydrocarbon value chains. It utilizes a pyrolysis reaction to generate hydrogen and solid carbon,[7] so there are no CO_2 emissions associated with the reaction.[8] The solid carbon by-product presents an interesting opportunity because it introduces a potential carbon-to-value proposition that can improve the commercial viability of the technology. Advanced carbon-based products derived from pyrolysis-based carbon materials could be used in applications ranging from construction, transportation, farming, while potentially displacing other CO_2-intensive materials. Despite important advances in material science, the use of advanced carbon materials is sectors like construction and transportation remain limited. It will be necessary to find alternatives use of the solid carbon if turquoise hydrogen is to substantially scale.

METHANE PYROLYSIS IN A HYDROGEN AND ADVANCED SOLID CARBON ECONOMY

Developing ways of capturing the carbon emissions from fossil fuels and upgrading them to higher-value products and materials presents an interesting commercial case for reducing emissions and meeting new energy demands without risking stranded assets and a complete re-engineering of the energy sectors. Processes that eliminate the production of CO_2 entirely, such as the direct conversion of methane in natural gas to hydrogen and solid carbon materials—e.g., methane pyrolysis—have gained traction among some major oil and gas companies.[9] As noted above, there are multiple technology pathways for low-carbon hydrogen, and each has its relative merits, with some likely more suitable in certain applications than others depending on regional factors.[10] Nevertheless, methane pyrolysis (turquoise hydrogen) could be particularly suitable to provide low-carbon hydrogen in regions with limited geological CO_2 sequestration sites, restricted access to renewable energy resources for water electrolysis, and legacy natural gas infrastructure.

Currently, 98%[11] of the 10 million metric tons (MMT) of hydrogen produced annually in the U.S. is done via steam methane reforming.[12] This process produces approximately 9.2 kg of CO_2 per kg of hydrogen.[13] In other words, the total emissions from current hydrogen production in the U.S. alone sum up to 92 million metric tons of CO_2 annually. For perspective, this represents roughly 2% of total U.S. CO_2 emissions.[14] With the demand for hydrogen set to expand substantially in the coming years,[15] opportunities exist for turquoise hydrogen to lead a low-carbon energy future.

As a key pillar of future energy systems, the opportunities hydrogen offers has prompted countries worldwide to integrate this versatile element into their energy strategies and development plans.[16] The policies and associated emission targets require low- to zero-emission hydrogen production, but the cost of production must be considered for long-term economic viability and competitiveness. For instance, the cost to produce hydrogen from alternative energy (green hydrogen) would have to decrease more than 50% by 2030 to make it a commercially viable alternative without government support.[17] Of course, technologies continue to improve and costs will come down, but certain technology options will inevitably be favored over others in different regions due to comparative advantages rooted in resource abundance, legacy infrastructures, policy, existing industrial footprints, and cost of alternative energy sources. Methane pyrolysis (turquoise hydrogen) can be a favored technology for any decarbonization strategy in regions with readily available, abundant, and affordable hydrocarbon resources and existing infrastructures with well-developed supply chains to produce zero-emission hydrogen and a competitive solid carbon material.

The value proposition of methane pyrolysis relies on the availability of sufficiently large markets that can absorb the solid carbon output that will result from the scale-up of turquoise hydrogen production.

SOLID CARBON USES: OPTIONS, CONSIDERATIONS, AND OPPORTUNITIES

The value proposition of methane pyrolysis relies on the availability of sufficiently large markets that can absorb the solid carbon output that will result from the scale-up of turquoise hydrogen production. Solid carbon can be used in applications that involve carbon black, graphite, carbon fiber, carbon nanotubes, and other derivatives. However, the estimated current market sizes for these products range from 20 thousand metric tons (kMT) for carbon nanotubes to 16.4 MMT for carbon black, which is by far the largest current market outlet. Summing up all the existing potential market outlets for solid carbon results in approximately 16.5 MMT.[18] This is grossly insufficient to absorb the potential output of solid carbon that would result if all current U.S. hydrogen production were to convert to pyrolysis. To wit, current hydrogen production in the U.S. is 10 MMT, meaning the market for solid carbon would need to be at least 30 MMT annually, or roughly double the current market capacity for non-combusted carbon produced without pyrolysis.

Thus, if hydrogen production is to be scaled to meet a significant portion of energy demand, the applications for a burgeoning carbon supply chain would need to move beyond traditional markets. The delta between the required market capacity and projected market size is indicative of the necessity to develop a value chain for solid carbon in order to facilitate large-scale deployment of methane pyrolysis. Either new market opportunities must open concomitantly with the scale-up of pyrolytic hydrogen, or storage opportunities must avail themselves until a robust carbon market can develop. In the longer term, it may be possible to develop pyrolytic processes to manufacture advanced solid carbon morphologies with controlled properties to displace current building materials with lower sustainability profiles, such as concrete and steel. The construction industry is, in fact, the only industry that could match the scale of the energy industry, and research and development activities are underway to create new pathways for carbon-based product development.

While such technologies could provide a long-term solution with very high CO_2 abatement potential, the timeline for large-scale deployment could be two to three decades into the future. The storage of solid carbon could provide an interim solution for the carbon produced from pyrolysis, allowing technologies to evolve while supply chains and markets mature, which will build a bridge to more advanced options for solid carbon utilization. However, akin to the challenge with CCS, carbon storage requires transportation and a storage facility, adding cost without creating value for the carbon. The concept of solid carbon storage as a decarbonization strategy is novel and would possibly require a new regulatory framework, reconfiguring of existing policies, and repurposing or development of new infrastructures.

SOLID CARBON "STORAGE" PATHWAYS

In order for turquoise hydrogen to be viable and competitive, the co-generation and sale of solid carbon as a feedstock into other processes is needed to accelerate commercial adoption.

Biochar, which is a pyrolysis byproduct from organic material, also can provide agricultural benefits by improving soil resilience, balancing pH, adding organic matter, increasing water-holding capacity, re-establishing microbial communities, and reducing soil compaction, and has positive benefits for air quality by reducing soil nitric oxide (NO) emissions.[19] In addition, improving soil health is a well-recognized pathway to improving soil's ability to retain carbon that is captured and transformed through photosynthesis of native vegetation. In turn, this provides a pathway to enhancing nature-based carbon solutions.

The existing research on the benefits of biochar opens the possibility of the use of solid carbon from methane pyrolysis as a soil amendment. Of course, there are still open questions. With regard to biochar, its quality as a soil amendment varies greatly with the feedstock materials, the pyrolysis conditions, and the type of soils amended.[20] Moreover, the evidence to date indicates a remarkably diversified set of results on capacities and efficiencies for the effects of biochar applications on mediating soil contaminants.[21] Given these variabilities, additional research is needed, but the possibilities certainly open interesting connections between pyrolysis of hydrocarbons, decarbonization of energy production and use, and enhancement of natural carbon sinks.

Research suggests that soil amendment through the application of biochar is a promising approach to mitigate soil contamination via immobilizing heavy metals and organic pollutants.[22],[23] For example, biochar can be used at EPA-designated Superfund sites, decommissioned military sites, former federal facilities, industrial sites with contaminated or disturbed soils, and other potential applications for reactive, relatively pure carbon matter. Contaminated soils that lack vegetation contain very little organic carbon, so they provide a promising potential for building soil organic matter and sequestering carbon. However, to date, there is a dearth of published research evaluating and quantifying terrestrial carbon sequestration benefits associated with remediation of contaminated lands through soil amendments.

Finally, it should be noted that other options for solid carbon are landfill applications or long-term storage in abandoned mines. Access to such sites may be readily available along existing rail infrastructure, thus removing a potential logistical challenge. However, such applications are not necessarily ideal or consistent with the principles of sustainability or a circular economy. Nevertheless, such pathways could be explored as short-term solutions as material science advances aimed at creating commercially viable pathways for utilizing solid carbon progress.

CLASSIFICATION OF SOLID CARBON AND THE NEED FOR DIFFERENTIATION AND DISTINCTION

Traditional grades of carbon black could be produced via methane pyrolysis, with the right reactor and process conditions. Indeed, it is commonly referred to as carbon black. However, carbon produced via methane pyrolysis is not the same as black carbon, which is produced via incomplete combustion of heavy petroleum products. This is an important note of distinction because black carbon is classified by the International Agency for Research on Cancer as a Group 2B carcinogen,[24] and it was added to the California Office of Environmental Health Hazard Assessment list of California Prop 65 substances known to the state to cause cancer.

Airborne particles containing elemental carbon are at the forefront of regulatory scrutiny (i.e., black carbon, carbon black, and engineered carbon-based nanomaterials).[25] Scientists, regulators, and the general public often group these carbonaceous particles together and use the terms interchangeably despite carbon black being a manufactured product with well-controlled properties and black carbon being an undesired, incomplete-combustion byproduct of fossil fuels and biomass with distinct physiochemical attributes and associated environmental, human health, and safety implications. The comingling of terms used synonymously for materials that are distinctly different could present erroneous analysis of safety risks and prevent solid carbon from pyrolysis from being applied for "beneficial use" in remediation or amendment pathways. It could also result in consumer skepticism, impeding solid carbon from gaining value in new markets or advancing to a value-added application that has the potential to displace or supplement energy intensive materials. Greater distinction is therefore required in the scientific literature and regulatory language. Carbon-based materials generated from methane pyrolysis are not equivalent to traditional carbon black, and the appropriate distinction is necessary so

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that they are not prematurely deselected from market opportunities.

In line with appropriately characterizing solid carbon from pyrolysis is the regulatory classification it ultimately receives. The management of solid carbon from pyrolysis is largely contingent on the regulatory classification of the carbon output, which could ostensibly push it into the "waste" category, setting it on an alternate path for special handling, treatment, and disposal. Classification as a hazardous waste, non-hazardous waste, by-product, co-product, spent material, secondary material, or non-hazardous secondary material all determine regulatory obligations as well as operational, engineering, and administrative controls, which include accumulation time, storage limits, training and reporting requirements, etc. Moreover, the classification of solid carbon will determine how it will be handled, where it can be stored, how it will be transported, and how and where it can be treated and disposed. None of this is settled.

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The entire matter is complicated by the fact that not all methane pyrolysis processes yield an identical carbon output. The quality, morphology, and chemical constituents of the resultant carbon material can differ depending on the type of methane pyrolysis technology employed (i.e., thermal, catalytic, plasma) as well as the operating parameters (temperatures, pressure, natural gas feed, methane conversion, reactor space, power, etc.) used in process. For example, side reactions during the pyrolysis reaction and the use of catalysts can produce saturated and unsaturated hydrocarbons and polycyclic aromatic hydrocarbons (PAH), which can present in the solid carbon state and be transferred to the final product. PAHs can be removed via solvent extraction, but they cannot be separated from the solid carbon by human biological processes. This can be a cause of concern from the standpoint of human health impacts of exposure. Although the impurities can be processed and removed at the point of generation or post-process, the economics of stabilization and removal may be cost prohibitive. Moreover, even if appropriate health and safety protocols are in place, public perception of toxicity may present a significant barrier to scale and, at the very least, will require a public communication effort on the true health concerns of solid carbon materials.

CHALLENGES AND OPPORTUNITIES

The challenges of developing a hydrogen and advanced solid carbon economy are vast and must be evaluated from a technical, legal, regulatory, and commercial standpoint in order to facilitate large-scale deployment of turquoise hydrogen. Identifying and appropriately addressing issues such as (1) negative public perception, (2) opposition to decarbonization strategies based on natural gas and hydrocarbons more generally, (3) a perceived risk of rising long-term natural gas prices, (4) the logistics of solid carbon transport, storage, and reuse, and (5) environmental, human health, and safety implications are all important considerations. Knowing what and where risks and potential barriers are and how to mitigate and/or overcome them to drive investment will help shape the future of innovative energy and materials production. It will also create viable pathways for solid carbon, with the ultimate goal of becoming a value-added specialty product that can be commercialized to offset the cost of hydrogen production by providing an additional revenue stream as an intermediate product for use in advanced materials with the potential to help accelerate climate and sustainability goals.

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