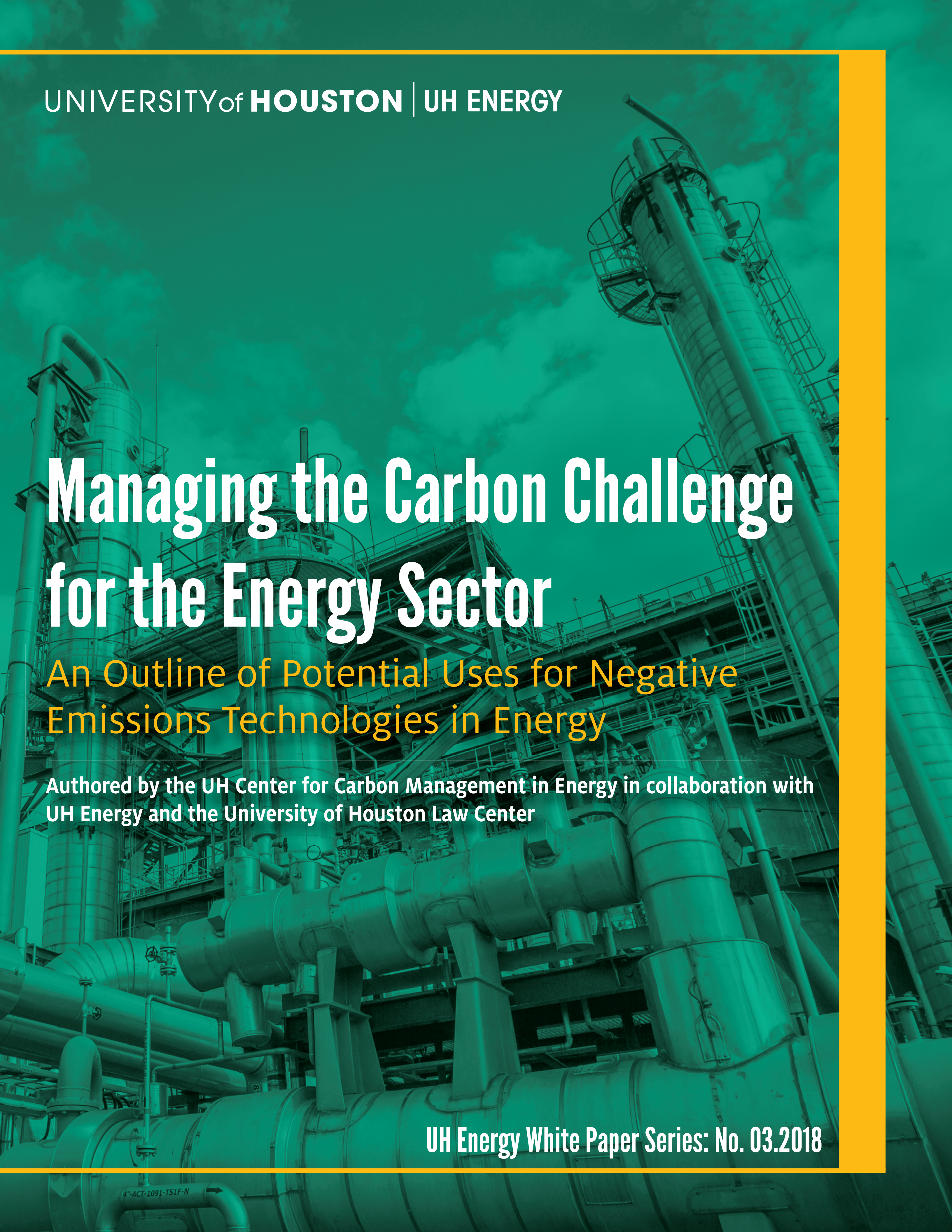

UNIVERSITY of HOUSTON | UH ENERGY

Managing the Carbon Challenge for the Energy Sector

An Outline of Potential Uses for Negative Emissions Technologies in Energy

Authored by the UH Center for Carbon Management in Energy in collaboration with UH Energy and the University of Houston Law Center

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EXECUTIVE SUMMARY

With little fanfare or public attention, negative emissions technologies (NETs) have grown into a key element of international and domestic strategies to combat the increasing concentration of atmospheric carbon dioxide (CO_2) and climate change. In particular, the vast majority of models which identify successful pathways to attain the Paris Agreement's 2˚ C goal (much less the more ambitious 1.5˚ C target adopted recently) relies heavily on negative emissions technologies. Even if mitigation efforts drastically reduce ongoing and future emissions of greenhouse gases, current concentrations of CO_2 in the atmosphere from past industrial activities would result in dangerous anthropogenic climate effects for centuries, if not millennia, into the future. While mitigation of ongoing emissions and adaptation to climate change impacts remain indispensable, negative emissions technologies offer an important strategy to reduce these existing accumulations of CO_2 in a timespan relevant to human wellbeing.

The potential use, integration and impact of negative emissions technologies within the energy sector, however, remain largely unexplored. Energy producers, both globally and in the United States, face increasing challenges to the central role of fossil fuels in their current business models, including attempts to limit the production and use of fossil fuels, to require limits on emissions of greenhouse gases from energy generation units, or force restatements of reserves to reflect the risk of "stranded assets" of carbon-based fuels. The development and deployment of commercially viable negative emissions technologies could therefore provide an important tool for the energy industry to manage its own greenhouse gas emissions and offset emissions from the use of its products that are otherwise difficult or impossible to control.

On September 14, 2018, the University of Houston hosted a workshop to evaluate the feasibility and aspects of integrating negative emissions technologies as a component of energy production strategies. The attendees evaluated both the technical aspects of incorporating negative emissions technologies into energy systems as well as the potential governance options that they might create in the near future. The workshop then concluded that negative emissions technologies could play an important role in the future strategy and business models for energy production, refining, and fuels distribution. Integrating these technologies into the industry, however, will require substantial additional research, careful attention to establishing a rationale economic system to incentivize negative emission operations, building a sufficient market or sequestration capacity to manage CO_2 and greenhouse gases captured by negative emissions facilities, managing potential conflicts arising from natural resource demands and land use challenges, and assuring sufficient transparency and public input to meet current standards for corporate social responsibility and sustainability practices in the energy sector.

BACKGROUND

Sudden Prominence of NETs

Negative emission technologies (NETs) are techniques that remove more CO_2 (or other greenhouse gases) from the ambient atmosphere than they emit. This broad definition includes strategies ranging from accelerated weathering, biochar, biological energy with carbon capture and sequestration (BECCS), afforestation, ocean iron fertilization, and direct air capture (DAC), each of which is described in greater detail in the Appendix. While these technologies adopt a broad array of approaches, each one seeks to absorb and utilize (or sequester) more greenhouse gases than it emits when evaluated over its entire lifecycle. For multiple reasons — including moral hazard concerns[1] and the relatively high costs, resource demands, accompanying negative environmental impacts, and possible land use conflicts of early iterations of NETs[2] — these technologies have received comparatively little attention in prior discussions over climate change options and policies.

Several trends point to the need for negative emissions technologies to respond to disruptive climate change. Fundamentally, the current elevated concentrations of CO_2 in the ambient atmosphere reflect over a century of anthropogenic emissions, and they will not readily drop even if current emissions dramatically decrease or completely cease. As a result, recent models that identify possible pathways which achieve the Paris Agreement's formal 2.0˚ C temperature target almost uniformly rely on negative emissions technologies.[3] Given the relatively slow reductions in emission rates of greenhouse gases, the need for negative emission technologies become even more pressing if the Paris Agreement parties hope to attain their more optimistic aspirational goal of 1.5˚ C.[4]

NETs and Energy

The U.S. energy industry, especially the utility electrical energy sector, the oil and gas exploration and production sector, and the refining sector, have not aggressively explored or implemented negative emissions technologies. While initial interest has focused on the use of carbon capture, utilization and storage (CCUS), particularly in conjunction with enhanced oil recovery, those technologies in their current forms

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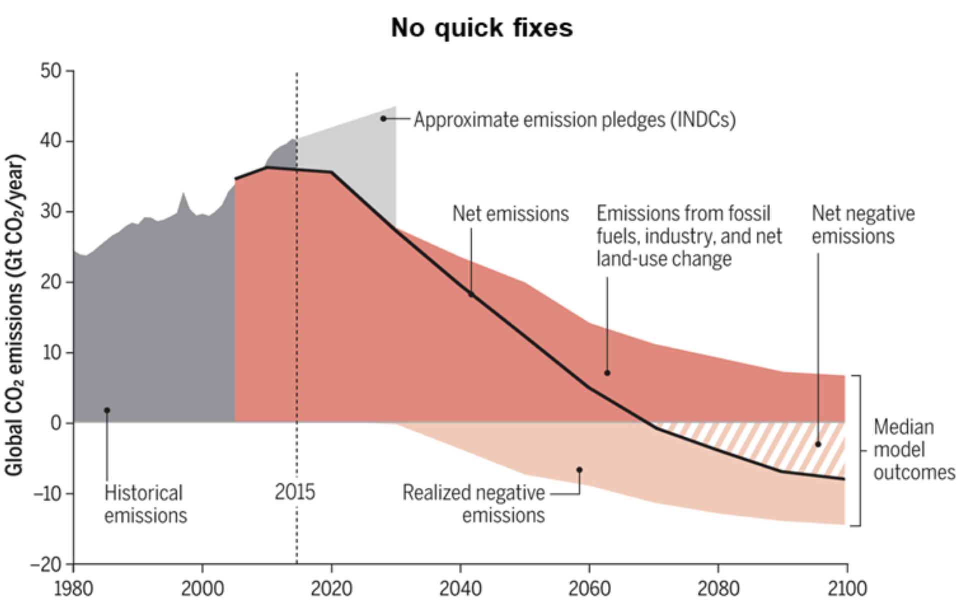


Kevin Anderson, and Glen Peters Science 2016;354:182-183

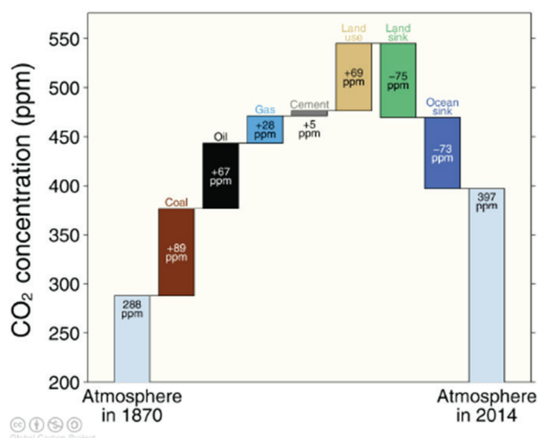
predominantly act as carbon-neutral platforms to capture new emissions at their point of generation. Rather than reduce existing concentrations of ambient greenhouse gases, CCUS therefore prevents the emission of additional CO_2 when producers burn or refine fossil hydrocarbons to generate electricity, fuels, or petrochemical products.

As a result, the possible role of negative emissions technologies in the energy sector remains largely unexplored even as the potential need for them in the production of energy has grown. Energy producers, both globally and in the United States, face increasing challenges to the central role of fossil fuels in their current business models, including attempts to:

- Limit the production and use of fossil fuels;
- Constrain emissions of greenhouse gases from energy generation units;
- Impose mandatory offsets or netting of greenhouse gas emissions, including from niche market uses that are difficult to directly offset (e.g., aviation fuels);
- Force restatements of reserves to reflect the risk of "stranded assets" of carbon-based fuels; and
- Disrupt financing provided for capital investment to construct new manufacturing and energy production facilities.

The energy sector offers several facets of special importance to negative emissions technologies. First, the industry faces the dual challenge of managing the impacts of carbon restraints on both the value and usability of its feedstocks (in particular, reserves of fossil hydrocarbon resources) and on its ability to use this feedstock inventory to produce, refine, transport, and distribute its products. Limits on emissions from fossil fuel consumption in particular may lead to constraints on the ability of hydrocarbon producers to explore and produce from their existing holdings. For example, one recent study concluded that attaining a two-degree C target would limit future emissions of CO_2 to approximately 800 gigatons; this limit would bar the future use of 20 to 40 percent of current fossil fuel reserves.[5] Second, reductions in emissions of greenhouse gases during exploration, production, and refining of hydrocarbons may require an increase of five to 15 percent in existing energy company capital expenditure budgets for European energy companies.[6] These limits could force a substantial restricting of the electrical generation and hydrocarbon refining processes themselves. The energy sector is currently investing heavily on managing its emissions, which also makes reducing emissions a waste management issue. Finding viable ways to rather utilize and transform this challenge into a profitable revenue stream in a climate constrained world is likely where the industry will find the most value.

Moreover, the energy sector also must wrestle with the potential impact of carbon restraints on the marketability of their eventual commercial product. Several energy-intensive commercial sectors — including aviation, shipping, cement production, and steel — will pose special challenges to attempts to reduce their carbon emissions, and these limits will cause secondary effects on the energy supplies demanded by them. While electricity consumers typically only focus on greenhouse gas emissions caused by the generation (not use) of electricity itself, some instances of



load-following electricity may also prove difficult to decarbonize.

Renewables and waste heat utilization will potentially have a larger role to play for energy intensive NETs, and the latter could ease the intermittency challenges that could thwart large-scale penetration of renewables. However, like any complex process, a seamless integration will largely depend on where and how system boundaries are drawn, eventually helping to consolidate NETs while paving the way for a hydrogen economy. Although energy producers agree that learning by doing requires doing, the transition is and will continue to be difficult to monetize unless there are pathways to revamp carbon management as a service-driven model rather than a compliance-driven model.

Last, the energy industry is the only one of a few industrial sectors that can manage this task at the scale required (outside of BECCS), and perhaps it is the only one that can immediately create economic value for recaptured carbon by capturing, utilizing and storing it for further use.

Other than federal tax credits for the use of captured CO_2 in enhanced oil recovery or other geological sequestration, the U.S. government has offered relatively limited funding to support research into negative emissions technologies overall. The growing importance of negative emissions technologies in future climate policy has led for several calls to increase the amount of federal grants and support for this area, including a major report from the National Academy of Sciences in September 2018.[7] The corporate community and academic researchers have added their voices in support for greater research in this area. None of these recommendations, however, have resulted in expanded funding or policy direction to support research on negative emission technologies, and these recommendations also failed to emphasize the need for greater research on how these negative emissions technologies might directly relate to or affect the energy industry.

Emerging Technological Pathways

Negative emission technologies can fall into a broad array of different approaches and methods (see Appendix). To explore the potential role that some of them may play in the energy sector, the workshop focused on three negative emissions initiatives that recently progressed to field demonstrations: high-volume direct air capture with chemical sorbents to sequester or use ambient CO_2 as a feedstock, the capture of CO_2 with contact polymers through low-energy absorption enabled through evaporation of water, and the production of emission-free or net negative emission electricity by using compressed heated CO_2 in lieu of nitrogen and steam. Each of these approaches offers promising possibilities for broader use in energy production and use, but each one also faces daunting technical challenges to achieve necessary cost reductions, improvements in reliability, and scalability.

Direct Air Capture in Energy Production

Direct air capture typically uses technological process, frequently chemical, to remove CO_2 from the ambient atmosphere and use it as feedstock or permanently sequester it. These processes offer the promise of scalability and speed to remove substantial volumes of CO_2 with relatively compact facilities, but available technologies remain costly and untested at large scales. In a recent report, the National Academy of Sciences identified five private companies that have begun either a demonstration plant, pilot plant, or laboratory work on NETs that could scale up for significant operations. Three of those companies already have NET facilities in operation.[8]

In particular, direct air capture technologies can help capture ambient CO_2 while providing

feedstock for carbon neutral liquid fuels. Carbon Engineering, for example, currently captures CO_2 from the atmosphere in an industrial-scale setting. The process captures up to one megaton of CO_2 annually by running pressurized ambient air through a bed of aqueous potassium oxide sorbent that feeds continuously into a calcium caustic recovery step to regenerate the sorbent and release the CO_2. Carbon Engineering's process yields a stream of high-purity CO_2 that it can either sequester, dedicate to enhanced oil recovery, or turn into a liquid hydrocarbon fuel.

The industrial scale of this process offers several important advantages. First, it allows the capture of a significant amount of CO_2 at a facility with a relatively small footprint. By contrast, other lower-energy processes rely on gentler pressure gradients over a broader surface area, and as a result they require larger amounts of land or space (as described below). Second, because CO_2 mixes and disperses quickly into the ambient atmosphere, this process can capture gas at locations removed from emission sources or other industrial operations. This feature enables industrial direct air capture to locate in remote regions with access to desired resources or energy supplies, and as a result operators can avoid some of the land use resource conflicts that bedevil other negative emission technologies such as BECCS.

This approach, however, suffers from important constraints. The process needs substantial amounts of energy to compress ambient air, regenerate sorbent, and maintain operating temperatures. Additional steps, such as creating hydrocarbon fuel from the captured CO_2, require even more power. As a result, industrialized direct air capture requires careful design to keep its energy demands from causing more CO_2 emissions than the process itself captures from the air. To minimize this risk, a DAC facility that uses fossil fuels such as natural gas to power its process may route emissions from that power source to its captured air stream. The growing prevalence of decarbonized power can also reduce this risk.[9] Second, industrialized DAC, by necessity, relies on complex and expensive capital machinery for its operations. As a result, it can be more costly than other technologies on a levelized basis.

A pilot plant constructed by Carbon Engineering in Squamish, British Columbia has investigated the performance of these processes and recently yielded sharper cost data. According to Carbon Engineering, the facility has captured approximately one ton per day of CO_2. Based on the facility's capture rate of one ton per day of CO_2 since 2015 and the capital costs incurred to construct and operate the plant, this process captures CO_2 at a levelized cost ranging from $94 to $232 per ton. The design required 5.25 gigajoules of gas and 366 kilowatt hours of electricity per ton of captured CO_2 (or, alternatively, 8.81 gigajoules of natural gas). This data gives a sharper view of potential costs of DAC, which prior reports had estimated across a broad range from $50 to $1,000 per ton of CO_2. The process also requires 4.7 tons of water for each ton of CO_2 that it captures under normal operating and environmental conditions. While Carbon Engineering's cost figure for its captured CO_2 includes the value of this water, the availability of ready water resources may constrain the suitable locations for future sizable DAC operations.[10]

This data highlights some of the key promises and challenges for current DAC technology. In particular, these results support the feasibility of using captured CO_2 to generate liquid fuels (including aviation kerosene). This specific demonstration plant, however, also used natural gas to power the DAC process. While the facility recaptured some of its own CO_2 emissions, future iterations will likely need to find locations with abundant renewable energy or zero-emission energy sources. The cost of liquid fuels generated by the DAC

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process currently remains higher than current market prices for mass market consumer fuels.[11]

Capture of Carbon Dioxide Through Moisture-Swing Absorption

Rather than an intensive process to capture and provide large volumes of CO_2 at high purity through industrial infrastructure, an alternative approach captures ambient CO_2 with a polymer absorbent that entrains CO_2 when wet. The capture process relies on ambient air movement and energy from evaporation, and the impregnated polymer releases the CO_2 when immersed into water. The facility operator would remove the CO_2 from the water. The process yields CO_2 at lower concentrations than concentrated processes that use compressed air, industrial power sources, and higher temperature gradients, but it requires far less power and costs far less per ton. The CO_2-enriched air generated by this process can be used for agriculture, manufacturing, or other uses.

This technological strategy would allow the placement of units at multiple locations to absorb ambient CO_2, and then collect them on a periodic basis to remove the captured CO_2 for utilization for sequestration. If each unit could capture up to one ton of CO_2 per day, an effective deployment of 10 million air capture units per year combined with a lifespan of 10 years would result in a steady-state capture rate of 3.6 Gt CO_2/yr that would exceed current anthropogenic CO_2 emissions.[12] While this number appears daunting, it compares favorably with the total number of automobiles produced globally on an annual basis or other large-scale industrial activities. Such a large-scale deployment would require substantive public involvement and financial support, which one speaker at the workshop estimated could total 22 cents more per gallon of gasoline.

Low-energy absorption swing technology powered by ambient air movement and transpiration, however, would also pose downsides. For example, the pace at which it removes CO_2 is slower than other technological processes, it would require larger amounts of dedicated land space than compact energy-intensive DAC operations, it demands substantial amounts of water, and it offers no immediately apparent co-location benefits with other industrial operations (including energy production and distribution).

Production of Zero-Emission Electricity Using Compressed Carbon Dioxide

In addition to technology dedicated primarily to capturing ambient CO_2 or other greenhouse gases, other forms of negative emissions technologies can remove ambient CO_2 as a side-benefit apart from their primary production purposes. This type of dual-purpose technology could play a critical role in the power generation sector.

The workshop examined one possible method to generate electricity that would rely on compressed heated CO_2 to drive turbine generators rather than conventional steam. Such an Allam cycle power plant would work at far higher efficiencies than a steam turbine system because CO_2 undergoes phase changes to drive the turbine without suffering thermodynamic losses (enthalpic penalties) at the same level as water. As a result, the turbine generates a small stream of excess pure CO_2 that can serve for other industrial purposes, including desulphurization of sour natural gas. Given that up to 40 percent of natural gas located outside of North America is sour, relatively small amounts of pure CO_2 – e.g., one ton — could generate large amounts of sweet natural gas — 100 million BTU per ton. This cost-effective path to sweetening natural gas would speed conversion of existing coal-fired power units to natural gas. In addition, the pure CO_2 stream generated by the Allam cycle power plant could provide the feedstock (along with sufficient cost-effective supplies of hydrogen) to produce methanol as

liquid fuel.

A demonstration plant constructed by NET Power in Pasadena, Texas has successfully demonstrated the feasibility of the unit used to combust natural gas in a pure oxygen environment. The tests included both a five megawatt and a 50 megawatt thermal unit. Based on initial results, NET Power predicts that it will be able to produce hydrogen for a cost of 35 cents per kilogram (if the system uses sour natural gas). The Allam process also generates significant amounts of heat that a production unit could harness for other purposes.

Governance and Regulatory Policy

Despite the forecasted need to remove substantial amounts of CO_2 from the ambient atmosphere on an annual basis by 2100, current international and domestic laws and policies do not facilitate — or even address — the hurdles posed to creating this enormous technological task. The primary international legal agreements that pertain to climate change, including the Paris Agreement, only tangentially refer to the use of carbon sinks and reductions in anthropogenic emissions via offsets. Other international instruments may pose regulatory or liability risks which could discourage some methods of negative emissions technologies (e.g., the use of the London Convention and London Protocol to limit the use of ocean iron fertilization). Domestic laws also do not explicitly address or facilitate research into negative emissions technologies or their broad deployment. These regulatory and liability barriers could prove significant. For example, some methods of negative emissions technologies will need substantial commitments of land, water, or other resources to operate at a scale required by current climate forecasts. BECCS, in particular, would demand the acquisition of substantial amounts of land and water to support the crops that would provide the feedstock for bioenergy facilities. By some estimates, reliance on BECCS alone to meet negative emission targets set out by the Paris Agreement would consume up to 40 percent of available arable land on a global scale. Approvals for some types of negative emissions technologies, such as ocean iron fertilization, could prove lengthy and difficult, and the creation and operation of sizable reservoirs to store captured CO_2 would pose daunting liability and regulatory challenges. The siting of significant arrays of DAC facilities, the assessment of their potential environmental impact, and the management and disposal of residues from DAC operations could also require governmental oversight and approval.

CONCLUSIONS

The workshop participants saw a possible role for negative emissions technologies in the energy sector, and several noted that the interest in such technologies had recently grown stronger by acknowledging that negative emissions technologies have garnered more interest in the last year than there has been in the last decade. Negative emission technologies could help the energy sector wrestle with several looming important challenges, including risks in stranded assets or capital investments, assisting the possible unavoidable extension of fossil fuel use during a transition to a low carbon energy economy, and assuring amelioration of climate change effects on a temporary basis if emissions overshoot the limits required to meet goals set out by the Paris Agreement or other international commitments.

Important questions remain, however, about how negative emissions technologies would be integrated into possible future methods of energy production. Most fundamentally, no economic market currently exists to create a recoverable value for CO_2 removed from the ambient atmosphere. Carbon pricing mechanisms and or market approaches can place a price on the emission of CO_2 into the atmosphere, and offset mechanisms in cap

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and trade or taxation could allow this "price" to be applicable to CO_2 removed from the air, currently in the United States these market mechanisms are spotty in use, and not large enough to provide a price signal.

The creation of such a pricing mechanism, either directly for recovered ambient CO_2 or through incorporating the use of negative emissions technologies in pricing systems for new or ongoing point source emissions, would provide an extremely important step in encouraging the development and deployment of negative emissions technologies. Establishing investment mechanisms, such as the Paris Agreement's provisions for internationally transferable mitigation outcomes, could potentially act as drivers for this integration.

Second, a vast mismatch of scale exists between the amounts of historical and current emissions of CO_2 with the potential markets or economic uses of the captured CO_2. The capture of ambient CO_2 in meaningful amounts would create an enormous inventory of CO_2 that would far exceed the existing markets for other industrial gases. For example, even if all worldwide polyethylene demand was satisfied through captured CO_2, that market would consume only 1 percent of the captured gas.[13] One workshop participant noted that the mass of CO_2 currently emitted annually exceeds the amount of sand and gravel produced on a global basis. While this challenge exists for any use of negative emissions technologies, it would pose a special challenge for the energy industry because it accounts for the large majority of industrial emissions of CO_2 and other greenhouse gases.

Third, the use or sequestration of CO_2 captured by negative emissions technologies could offer potential benefits and competitive advantages to the energy sector. The knowledge developed through tests on carbon capture usage and sequestration at large industrial facilities will apply as readily to negative emissions facilities that collect ambient CO_2. As a result, the hydrocarbon exploration and production sector can draw on a ready baseline of knowledge about geologic reservoirs for sequestration from its prior work on fossil fuel development, and the refining sector can adapt its existing process expertise to the development of liquid fuels from captured CO_2.

Fourth, the use of negative emissions technology in the energy sector will need to navigate the conflicts created by natural resource demands (in particular, water consumption), siting and land use conflicts, and disposal of process residues and captured CO_2. The energy industry has great familiarity with these issues and can integrate its assessment of these concerns with its development of negative emissions capacity and infrastructure.

Last, the broad development and integration of negative emissions technologies into energy production will likely spark public concern and demands for transparency. The energy sector will need to adapt its current consideration of corporate social responsibility and social license to operate to accommodate public disclosure and input during the construction and siting of negative emissions facilities that will likely provoke special concerns, especially during the early stages of implementation when the public will be unfamiliar with the technology.

APPENDIX

AFFORESTATION:
Planting trees in an area that previously lacked them, typically on a systematic and sizable scale. By contrast, reforestation is restoring areas where trees have been cut down or degraded.

Uncertainties and Barriers: Land availability and suitability. Effect on crop yields, farmers, and agrarian economies. Water requirements.

BIOCHAR:
Biochar is a charcoal-like carbon material produced by the controlled thermal decomposition of organic materials such as wood, manure or leaves, in a low-oxygen environment and at relatively low temperatures. While this process mirrors the production of charcoal in many respects, biochar – unlike charcoal -- is primarily used as a soil amendment to improve soil functions and to reduce greenhouse gas emissions from biomass that would otherwise naturally decompose.

Uncertainties and Barriers: Availability and use of land to produce organic materials. Water demand. Duration of sequestration of carbon in biochar. Scalability.requirements.

BECCS:
Achieves net negative emissions from the integration of trees and crops with carbon capture and sequestration (CCS). As biomass grows, it draws CO_2 out of the atmosphere. This biomass is then burned in power plants to produce energy, and the facility then stores the resultant CO_2 emissions via CCS.

Uncertainties and Barriers: Competition with food crops and biodiversity conservation. Increased land and water usage. CCS storage capacity and location considerations. Financial and technological scale-out barriers.

BLUE CARBON HABITAT RESTORATION:
Marshes, mangroves, and seagrass beds act as natural carbon sinks by capturing CO_2 from the atmosphere and storing them. The carbon thus stored in coastal or marine ecosystems is known as 'blue carbon'. Blue carbon habitats are known to sequester carbon at a faster rate than forests.

Uncertainties and Barriers: Data on carbon sequestration rates, on-site storage, emission profiles, and cost uncertainties.

BUILDING WITH BIOMASS:
Using plant-based material for construction in a way that stores and preserves carbon for the lifespan of the building. For example, this technique can use timber and bamboo for structural elements, hemp and wool for insulation, and hemp-lime for walling. These biological materials provide an alternative to standard construction materials, including steel and concrete, which are typically carbon-intensive to produce. Natural materials have additional benefits such as the ability to regulate moisture and absorb pollution.

Uncertainties and Barriers: Lack of investment, certification, and expertise currently impede large-scale deployment. Current regulations for buildings and construction efforts conflict with required developmental support.

DIRECT AIR CAPTURE:
Pulls and captures CO_2 out of the ambient atmosphere. The removed CO_2 can then be buried underground or used in chemical processes to produce alternative products for commercial use.

Uncertainties and Barriers: Financial and technological scale-out barriers. Need for large supplies of carbon neutral power to assure that DAC processes remain carbon-negative over their entire life cycle. Potential water and land use conflicts, depending on the DAC technology selected.

OCEAN IRON FERTILIZATION:
Injecting nutrients, such as iron, into nutrient-poor marine regions can trigger a bloom of phytoplankton whose enhanced photosynthesis would absorb CO_2. This method could also decrease the amount of dimethyl sulfide that marine organisms release, which can alter the reflectivity of clouds and alter warming.

Uncertainties and Barriers: Environmental and transboundary concerns. Questionable effectiveness. Current cost estimates are considered incorrect by certain groups. Social accepta¬bility is low, and some nations classify the practice as oceanic dumping of wastes considered illegal under international conventions.

ENHANCED WEATHERING (Terrestrial and Oceanic):
Terrestrial: The process begins with rain, which is usually slightly acidic because it absorbs CO_2 from the atmosphere on its journey to the ground. The acidic rain reacts with the rocks and the soil that it lands on, gradually breaking them down and forming bicarbonate in the process. Eventually, this bicarbonate washes into the oceans, where the carbon is locked up in the sea floor. Enhanced weathering accelerates this process by spreading crushed silicate material onto large surfaces.

Oceanic: The process proposes adding chemical carbonates to ocean waters to theoretically increase their alkalinity and therefore their carbon uptake.

Uncertainties and Barriers: Environmental and energy impacts from producing minerals needed for enhanced weathering. Competing or conflicting land use demands. Impacts on water systems that receive runoff from enhanced weathering areas. Impacts on water resources and water quality. Uncertainty about rates of dissolution of minerals, transport into ocean systems, and uptake of CO_2 from the ambient atmosphere.

FOOTNOTES

1 – Mace, M.J., Fyson, C.L., Schaeffer, M. Hare, W.L., *Governing large-scale carbon dioxide removal: are we ready?*, Carnegie Climate Geoengineering Governance Initiative (C2G2) at p. 32, (New York, US Nov. 2018); D. Sandalow et al., *Direct Air Capture of Carbon Dioxide: ICEF Roadmap 2018* at p. 20 (ICEF Dec. 2018); J. Minx *et al., Negative Emissions – Part 1: Research Landscape and Synthesis*, Envt'l Research Letters at pp. 5, 19-22 (May 2018), https:doi.org/10.1088/174-926/aabf9b .

2 – For example, the American Physical

Society released an influential early report that concluded a large DAC facility would cost $600 or more per metric ton of captured CO_2. The American Physical Society, APS Panel on Public Affairs, *Direct Air Capture of CO_2 with Chemicals: A Technology Assessment for the APS Panel on Public Affairs* (June 1, 2011). In a similar vein, the National Research Council of the National Academies National Research Council of the National Academies concluded that removing significant volumes of CO_2 with DAC could require up to 100,000,000 acres of land in the Southeast United States. This figure assumed, however, that the DAC units would rely solar on solar power sources that themselves require large amounts of surface land. Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration at 58, 62 (2015).

3 – K. Anderson and G. Peters, *The trouble with negative emissions*, 354 Science 182 (Oct. 14, 2016) ("Yet when it comes to the more stringent Paris obligations, studies suggest that it is impossible to reach 1.5˚ C with a 50 chance without significant negative emissions. Even for 2˚ C, very few scenarios have explored mitigation without negative emissions.")

4 – IPCC, 2018: Summary for Policymakers. *In: Global Warming of 1.5˚ C. An IPCC Special Report on the impacts of global warming of 1.5˚ C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty,* at p. 19 ("All pathways that limit global warming to 1.5˚ C with limited or no overshoot project the use of carbon dioxide removal (CDR) on the order of 100-1000 Gt CO_2 over the 21 century.")

5 – M. Masnadi *et al., Global carbon intensity of crude oil production,* 61 Science 851, 853 (Aug. 31, 2018); C. McGlade and P. Ekins, *The geographical distribution of fossil fuels unused when limiting global warming to 2˚ C,* 517 Nature 187 (Jan. 8, 2015), doi:10.1038/nature14016.

6 – K. Gilblom, *JPMorgan Warns Oil Industry Faces Huge Costs to Reach Climate Goals,* Bloomberg News (Sept. 11, 2018), https://www.bloomberg.com/news/articles/2018-09-11/big-oil-seen-facing-monumental-costs-to-reach-climate-goals.

7 – NAS NET Research Agenda at 14.

8 – NAS NET Research Agenda at 133-34. The three companies with operating DAC facilities are Climeworks, Global Thermostat, and Carbon Engineering.

9 – Carbon Engineering adopted this strategy with its Squamish test plant. D. Keith, G. Holmes, D. St. Angel, and K. Heidel, *A Process for Capturing CO_2 from the Atmosphere*, Joule 2, 1-22 (Aug. 15, 2018), https://doi.org/10.1016/j.joule.2018.05.006.

10 – Id. at 9.

11 – For example, Carbon Engineering estimates that its technology, once fully scaled up, could produce fuels for less than $1 per liter, or roughly $3.79 per gallon. http://carbonengineering.com/about-a2f/ (under "Cost competitive" discussion). By comparison, consumer commercial gasoline in the United States sold for an average of $2.37 per gallon on December 18, 2018. https://gasprices.aaa.com/state-gas-price-averages/ (figures compiled by the American Automobile Association). Gasoline prices in California on that date totaled $3.40 per gallon because its laws and regulations impose more stringent emission and carbon emission standards for fuels. *Id.*

12 – K. Lackner et al, *The urgency of the development of CO_2 capture from ambient air,* 109 PNAS 13156, 13159 (Aug. 14, 2012), www.pnas.org/cgi/doi/10.1073/pnas.110876109 ; S. Schrage, *Technique doubles conversion of CO_2 to plastic component* (May 18, 2018), at https://phys.org/news/2018-05-technique-conversion-co2-plastic-component.html; S. Ahn *et al., Poly-Amide Modified Copper Foam Electrodes For Enhanced Electrochemical Reduction of Carbon Dioxide*, 8 ACS Catal. 4132-4142 (2018), doi: 10.1021/acscatal.7b04347.

13 – See, e.g., A. Otto, T. Grube, S. Schiebahn, and D. Stolte, *Closing the loop: Captured CO_2 as a feedstock in the chemical industry,* 8 Energy Environ. Sci. 3283, 3283-84 (2015), doi: 10.1039/c5ee02591e.

About UH Energy + CCME + EENR Center

UH ENERGY

UH Energy is an umbrella for efforts across the University of Houston to position the university as a strategic partner to the energy industry by producing trained workforce, strategic and technical leadership, research and development for needed innovations and new technologies.

That's why UH is THE Energy University.

CCME

The Center for Carbon Management in Energy works to identify and develop possible carbon management strategies applicable during the production, management, and distribution of energy resources and products. These carbon management strategies include, but are not limited to, carbon capture and utilization during energy production and distribution as well as negative emissions technologies.

EENR CENTER

The Environment, Energy & Natural Resources Center at the University of Houston Law Center links energy issues with impacts on environment and natural resources. Building on the academic excellence of the faculty in these areas and the complex and multi-faceted energy and environmental issues in Houston, the Center provides a forum for education and discussion of the most important issues of the day, such as climate change, air pollution, clean coal and renewable energy.

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