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APPENDIX: TECHNICAL AND COMMERCIAL STATUS OF CARBON MANAGEMENT

Net-zero Framework: Climate and US Competitiveness

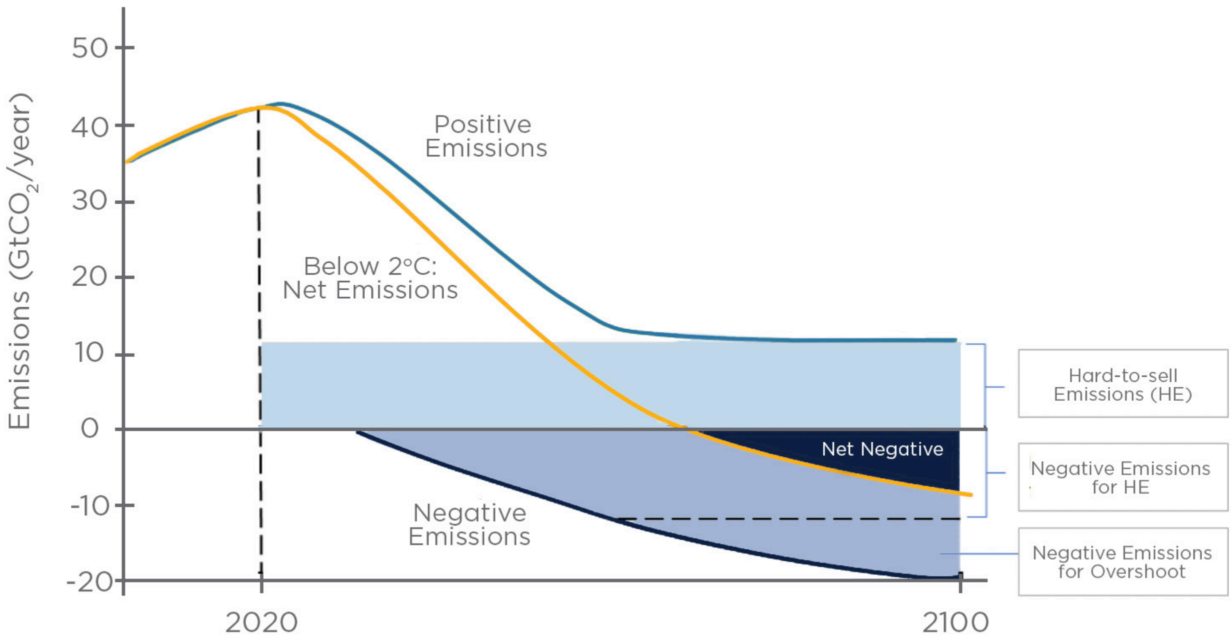
By definition, achieving net-zero emissions requires that any emissions that are not *reduced* must be *removed*. Emissions reduction and removal are distinct in nature and are different from emissions avoided:

- *Avoided emissions* are those that might have occurred but do not (for example, by not building a steel-mill due to overcapacity or by building a solar PV power station instead of a natural gas generation).
- *Reduced emissions* are existing emissions that no longer occur. Emissions may be reduced through many means, including conservation, efficiency, carbon capture & storage, or by shutting down or displacing existing emissions sources.
- *Removed emissions* are those that were emitted and are retrieved from the air and oceans. These can be from natural processes (e.g., mineral weathering), managed ecosystems (e.g., afforestation) or engineered systems (e.g., bioenergy with CCS).

To achieve net-zero emissions, all emissions trajectories must decrease (figure 1). However, if there are any residual emissions that are not reduced or mitigated, net zero requires an equal mass of CO_2 removal. In many scenarios and descriptions, residual emissions are considered “hard-to-abate”, meaning either the cost is extremely high (e.g., for aviation) or the technology does not exist (e.g., application of fertilizer). This is the core arithmetic of a net-zero emissions plan: ***any residual CO_2 emissions must be balanced by an equal amount of CO_2 removal.***

$$CO_2\text{emissions} - CO_2\text{removals} = 0$$

Figure 1: Representative pathway to net-zero and net-negative emissions. The orange line represents emissions trajectory as the sum of the green and blue trajectories



Source: J. Wilcox et al. 2020.

However, most analysis finds that it is not possible to achieve zero-emissions soon enough to stabilize global average temperature below 2 degrees Celsius through reduction alone. In particular, the IPCC found that to achieve emissions consistent with a 2°C limit to man-made warming would likely require 85% emissions reduction by 2050 and annual removal of gigatons CO_2 before 2100. To limit man-made warming to 1.5°C, 100% emissions reduction and annual removal of 5-10 gigatons CO_2 must occur around mid-century.[1]

By 2050: CO_2emissions(residual) - CO_2removal < 0

After 2050: CO_2emissions(residual) - CO_2removal = (-5 to -10 Gt/a)

The scale of the problem

When it comes to climate change arithmetic, the numbers are staggering and hard to understand or internalize. To help understand the numbers, it's useful to understand the nature of a gigaton.

- **All the people on earth combined weight roughly 1/2 a gigaton.**
- **The global annual production of plastic is about one gigaton**
- **Global consumption of meat is ~1/3 a gigaton.**

Unsurprisingly, managing many gigatons of emissions is extremely daunting. For example, the global oil market is roughly 5 Gt of material. To remove 5 Gt of CO_2 from the air and oceans requires an industry the size of the oil and gas industry operating in reverse.

This core arithmetic produces difficult corollaries. For example, the hard-to-abate sectors commonly are expressed as an irreducible annual sum of 8-10 Gt CO_2e. The persistence of residual emissions is founded on the lack of alternatives, especially for land-use emissions, shipping, and aviation. Although some analysis has laid the foundation for innovation and progress in these arenas (e.g., ETC, 2018), the lack of realistic plans for deployment means that these emissions appear across almost all analyses. Other difficult corollaries include:

- Any failure to reduce emissions must be balanced by CO_2 removal. For example, a failure to scale-up renewables, efficiency improvements, or EVs will lead to a larger removal burden.
- Achieving an 85% reduction in greenhouse gas emissions by mid-century requires a 50% emissions reduction each decade between now and 2050. Given the long capital lives of existing infrastructure and facility stock, it is not clear how this might be achieved.
- A 1.5°C trajectory requires 5-10 Gt removal by 2050 and greater volumes thereafter. The National Academies (2018) find that this is not possible through reforestation alone given the limits of land and current technology.

The core arithmetic produces an uncomfortable finding: existing capital stocks will overwhelm 1.5 or 2°C carbon budget. The IEA (2018) analyzed the global energy infrastructure either built or under construction. Assuming a natural capital life for facilities, just the existing capital stocks would emit 95% of the CO_2 emissions allowable under their sustainable development scenario, which is roughly 2°C of warming, and a 1.5°C budget was not possible without 100-1000 Gigatons of CO_2 removal by 2100.

Carbon Capture and Storage (CCS)

CCS represents a set of technologies that capture & separate CO_2 from large point sources, transport them to sites of geological storage, compress & inject them deep in the earth's crust, and monitor them to validate safe and secure storage operations. Today, 21 large-scale CCS facilities operate worldwide, safely and securely keeping more than 40 million tons of CO_2 from the air and oceans every year. In total, the world has managed more than 260 million tons of man-made CO_2 this way.[2]

Figure 2: Global CCS Facilities. Source, GCCSI 2019

CCS can and will play a critical role in managing the emissions from these key sectors:

- Heavy industry, including cement, steel, chemicals, refining, ethanol, pulp & paper, and glass[3] Application of CCS to these industries captures both process emissions and heat-related emissions. Of the 21 facilities capturing CO_2 worldwide today, 19 of them are on heavy industry.[4]
- Existing power stations, most notably coal- and gas-fired electricity production. Although some of existing fleet will be retrofit in the U.S.,[5] the majority will be in developing nations, notably in Asia.[6] This is an enormous market opportunity for US companies as part of industrial policy (see below).
- Production of low-carbon and zero-carbon hydrogen (commonly called "blue" hydrogen), as is currently done in five facilities worldwide,[7] including the Air Product project in Port Arthur, Texas. Today in the U.S., blue hydrogen production with low-cost natural gas costs only 20-60% more than unabated hydrogen production and is 2-4x cheaper than "green" hydrogen made with zero-carbon electrolysis.

Although these applications are very important for the US, they have enormous potential applications in China, India, Southeast Asia, Europe and the Middle East. These provide commercial opportunities to US manufacturers and companies to provide carbon management goods & services, as detailed in a recent NPC report.[8]

CO_2 Use and Recycling

For good reasons, many seek to find ways to use CO_2 to create economic value in a climate-positive way. Today, the primary use of CO_2 is for enhanced oil recovery. This is an important near-term pathway and provides opportunities to finance projects, scale-up technologies and reduce costs. Many see the value in turning CO_2 into goods for scale - that will be essential at some point for a circular carbon economy.[9] The three main types of valuable products made from CO_2 are:

- *CO_2-based cement & aggregates:* these are thermodynamically favored, and over 50 companies existing today that sell products into these markets, including US based Solidia Tech and Canada-based CarbonCure. This market is valued at over $1 trillion,[10] and could realistically accept as much as 1-2 Gt CO_2 each year.
- *CO_2-derived fuels and chemicals:* This would include intermediate chemical feedstocks like carbon monoxide, syngas & methanol.[11] The total market size is greater than $4 trillion, most as synthetic fuels, and could absorb 1-3 Gt CO_2. Depending on the feedstock and process life-cycle analysis, these could be carbon neutral or even carbon negative and could serve as alternative drop-in fuels, especially for hard-to-abate sectors (e.g., aviation and shipping). However, they require very large amounts of zero-carbon heat and electricity to synthesize. Many US companies large and small, including BASF, 3M, and Opus-12, are developing these technologies and products.
- *Durable CO_2-based-products:* including solid, stable carbon including carbon black (which goes into tires), carbon polymers, carbon fiber, carbon nanotubes, graphene and other graphitic materials, and carbon composites. These are long-lived forms and would keep carbon out of the atmosphere for centuries, and which may someday serve as cost-effective substitutes for steel and other emissions-intensive materials. Several US companies, including Monolith, Solid Carbon Products, NewLight, and Novomer, are developing and selling these materials.

Ultimately, it is unlikely that these approaches and products will lead to profound GHG emissions reductions. However, many nations (including Canada, Denmark, UAE and the Netherlands) are investing in development and market entry of these approaches as a deliberate industrial policy. CO_2 conversion, reuse, and recycling are potential engines for growth and are already supporting hundreds of US companies making and selling these products.

CO_2 Removal

Driven in part by the science, market forces and arithmetic discussed above, CO_2 removal has gained dramatic and profound increased prominence as an enterprise and as a necessary component of climate action. The National Academies has described the different pathways and what is needed for them to scale and succeed,[12] including substantial Federal investments in innovation, development, and demonstration.[13] They include both engineered and managed ecosystem approaches, both of which are more advanced than commonly realized and both of which would create jobs and opportunities at home and abroad.

Engineered pathways

These approaches use machinery and conversion equipment to separate CO_2 from ambient air. Three approaches appear to have the highest potential market application and potential:

- *Direct-air capture with storage (DACS):* This approach separates and removes CO_2 from ambient air. When combined with geological CO_2 storage, it withdraws CO_2 from the air and ocean permanently.[14] When combined with CO_2 use and recycling, DAC can provide a zero-carbon feedstock. There are seven DAC companies, with plans under development for projects in West Texas (Carbon Engineering + Occidental Petroleum), Huntsville, Alabama (Global Thermostat & Coca-Cola), and others. One Swiss company, Climeworks[15] has 14 operating DAC facilities and has offers commercial CO_2 removal services using DACS. Analysis reveals that modest investments and policy support would lead to dramatic cost reductions, remove millions of tons CO_2 every year, and create hundreds of thousands of jobs in the coming decades.[16]

- *Bioenergy with carbon capture and storage (BECCS):* This process involves harvesting plants that have removed CO_2 from the air and oceans and combining them with conversion, energy production, and geological CO_2 storage. When done correctly, BECCS is able to create low-carbon, zero-carbon, and even net-negative hydrogen, fuel, and chemicals by transferring CO_2 from the air to the geosphere.[17] The US currently has one operating BECCS facility (the ADM ethanol plant at Decatur, IL) with many more announced projects in Texas, California, and North Dakota.

- *Carbon mineralization (CMin):* Over very long timescales, CO_2 reacts with silicate minerals at the earth surface to make carbonate minerals. Humans can accelerate this process by adding heat and energy, grinding reactive rocks to increase surface area, or by combining air with the most reactive mineral fractions in the subsurface.[18] This binds CO_2 in mineral form. The enormous volumes of reactive minerals at the earth's surface and near subsurface make the volume potential for carbon mineralization effectively limitless. Recent work has identified locations where mineral resources, low-carbon energy, and existing infrastructure are available to support carbon mineralization projects.[19]

One additional approach to engineered pathways is ocean alkalinity enhancement.[20] Although important, and recommended by Energy Futures Initiative as a focus for innovation investment, deployment today faces challenges from international law and public acceptance that also merit continued work and attention.

Managed Ecosystems

Sometimes called "nature-based solutions" or "natural climate solutions,"[21] managed ecosystems involve changing land-management practices to increase standing stocks of carbon in living biomass within complex ecosystems.[22] Two overarching approaches are most commonly discussed:

- *Forest-based approaches:* These include adding new forests (afforestation), restoring recently lost forests (reforestation), avoiding deforestation, and enhancing the carbon uptake of working forests through new practices.
- *Soil-based approaches:* These include modifying agricultural practice in farm and grazing lands, including no-till farming, adaptive multi-paddock grazing (AMP), growth of cover crops, shifting to perennial crops, and adding trees to the margins of agricultural land.

In addition to removing CO_2, these approaches often have ancillary benefits (e.g., improving water quality, sustaining biodiversity, increasing soil health etc). However, substantial questions remain around accurate accounting of carbon uptake, particularly in soils. ARPA-E has a program[23] dedicated to improving accuracy and reducing costs of soil carbon monitoring, which today are estimated to be $1000's per ton.

Many companies, including technology companies (e.g., Pachama, Indigo, LandLife), are executing projects in the US and seeking to expand their markets. In some cases, these projects receive certification through qualifying registries, such as American Carbon Registry (ACR), Verra, Gold Standard, and Climate Action Reserve (CAR).

There are additional approaches to managed ecosystem pathways, including "blue carbon" (adding mangroves to coast waterways, wetland restoration, enhanced peat production, enhanced terrestrial or oceanic uptake (e.g., through genetically modifying plants[24] or cultivating macroalgae like kelp), amendment of soil systems with biochar.[25] These approaches are promising but have not yet reached the level of maturity necessary to easily enter the market today. This also suggests an innovation and scientific agenda[26] to further explore their potential and to accelerate their entry into voluntary and regulatory markets.

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