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Executive Summary:

There are many steps that humanity needs to start taking to address the growing crisis of environmental disaster. The immediate task is discovering ways to reduce the amount of damage done each year: this includes resource protection, industrial waste management, promotion of efficiency improvements in energy, transportation and construction. Even with these necessary reductions, there is an established need for technologies that can actively remove CO_2 from the atmosphere at the rate of one gigaton per year by 2030. Today in 2020, we are just entering the megaton scale of capture, meaning that there is a need to effectively double the capacity of carbon capture every year for the next ten years. Startups have been a successful method of inventing and scaling new technologies, as well as incentivizing involvement from talented individuals across diverse professional domains..

The goal of this document is to survey the existing approaches of carbon capture and to do the rough calculation of business viability of utilizing the result of the carbon capture in various markets. Simply put, if the lowest cost of carbon capture is currently $100/ton (as established by David Keith et al), what possible uses could produce more than $100/ton of value? Government grants, philanthropy, and other forms of non-dilutive funding are necessary to develop the technologies of the future, but in many embodiments, scaling the applications of these technologies to billions of tons would require some path to economic sustainability.

Success of this living document is identifying promising markets and mapping the necessary development to the desired technology. Identifying those markets and technologies is still in progress, but a few promising directions are highlighted. Furthermore, since this project was started, there have been many good reviews of negative emissions technologies published in good places, and they are cited in this document. What this attempts to do is one step beyond a review: being willing to make speculations about future technologies and identify valuable, high-leverage subproblems.

To all future readers, please feel free to add comments and suggestions! I have kept this document in a google docs because I think gDocs are the most dynamic for adding in new questions and suggestions from readers using the “Add Comment” feature. It is a publicly accessible link for a reason: please feel free to share. Already there have been awesome conversations sparked over the content in this document, and I hope for many more in the future.

-Dan and all contributors to date

Introduction

The IPCC has declared negative emissions technologies (NETs) to be an essential component of the climate goals (Obersteiner et al. 2018), in amounts of 10 - 20 gigatons of carbon dioxide per year out of the atmosphere within 20 years. Yet there are no current techniques that have a clear scaling trajectory to capturing a single gigaton of carbon dioxide per year. For reference of scale, the world’s forests sequester a net 2 gigatons of carbon dioxide per year (Bellassen and Luyssaert 2014). While there are interesting approaches, including direct air capture (DAC) and Bioenergy from Carbon Capture and Storage (BECCS), these approaches have limiting factors of cost and physical footprint, respectively. While it’s clear that technological iteration will be necessary, it is unclear where funding will be sourced for technological development, or for the billions of dollars in marginal cost once the technologies are physically able to operate at scale. The first sound business plan based on atmospheric CO2 as a feedstock remains elusive: The holy grail of fighting climate change is to discover a way to make it profitable.

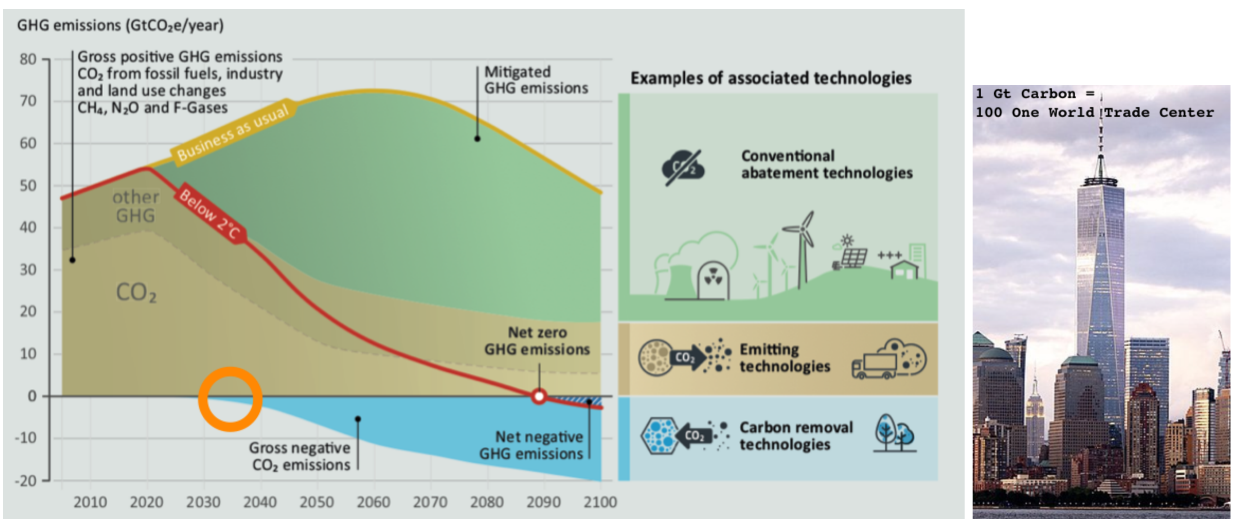

Figure 1 | Timeline and scale. The general consensus of the models is that humankind will need gigaton-scale sequestration operating by 2030, shown with the orange circle. For scale, 100 One World Trade Center towers is on the order of volumetric magnitude of a gigaton of pure solid Carbon (dry ice is ~1.6kg/m^3).

The NETs field is stuck between the metaphorical rock and a hard place. We know they are necessary because 87% of IPCC models indicate the need for carbon dioxide removal (CDR), in addition to other strategies, to maintain global average temperature increase below the 2^{o}C goal (Obersteiner et al. 2018). Thus, on one hand, we know that the best projections of carbon capture produce price tags of over $100 Billion per gigaton ($100/ton multiplied by a billions tons)- a cost which, even if the technology were ready for such scale, no government would pay today. But, on the other hand, there are no current economic prospects for carbon capture and utilization (CCU) to be more than ~4-8% of the total sequestration challenge (Mac Dowell et al. 2017). Beyond just the technology to physically remove the carbon dioxide from the atmosphere, there needs to be a financial design and exploratory element in order for gigaton-scale CDR to be feasible.

Is Carbon Dioxide a waste stream or a valuable commodity? This is a question that the best work in CDR technology has only begun to rigorously address: Although a 2018 tax bill did create an incentive of $50/ton of buried CO_2 via the 45Q tax credit (Temple 2018), that's still less than the current cost projections of leading CDR technologies.

It is worth acknowledging that there is a good argument to be made that worrying what to do with the sequestered carbon is currently out of scope of the pressing urge to develop the capture technologies in the first place. From the engineer's perspective, all good systems are modular systems, and getting the carbon down out of the air in the first place may be the most important part. Another similar argument to ignore financial concerns is that the future markets for the sequestered carbon don't even exist yet. I respect these arguments, yet I also contend that another path to technological development is a series of self-sustaining smaller steps. This is the startup approach. Future markets won't simply materialize, we have to create them ourselves.

This paper aims to tackle negative emission technologies from the entrepreneur's perspective. To do so, we will start with the necessary disclaimer that NETs are only part of a holistic solution of greenhouse house gas (GHG) reduction, then frame the problem as a profit-seeking entrepreneur would: surveying the market and identifying opportunities.

The Disclaimers

I am not a climate scientist and I respect those that are. Depending on NETs is a "last ditch" push to augment the society-scale changes that were prescribed to us decades ago if we are to stay within the 2^{o}C threshold. My narrow focus on negative emissions technology is not because I undervalue the importance of other fronts such as international mitigation policy and improved climate modeling, but rather because I have high confidence in the experts in that field. To support them, I read the papers, vote and donate and urge all readers to do the same. The part of the global challenge where I feel my personal maximum leverage is the intersection of science, engineering and business, and to scale NETs to gigaton will require all three.

Focusing on NETs is important but it requires three specific disclaimers:

1. NETs are not a license to pollute, nor to continue on the "business as usual" track. In the course of writing this paper I have seen interest groups place an incorrect angle on NETs. NETs should always be viewed as a component to holistic climate fixing strategy.
2. It is unreasonable for NETs to sequester every ton that humans emit. For example, with rough numbers, just a 1% reduction in transportation emissions is on the order of 100MT CO_2, which could be done within a year, which is a bigger net improvement to the atmospheric levels than NETs will do in the next ten years.
3. NETs technologies must work alongside climate scientists, not against them. Technology built for technology's sake is a failure mode of Silicon Valley. As one famous example, consider Juicero, an over-engineered $400 juice-making robot that vaporized $120MM of investor capital (link, engineering analysis here), building a beautiful machine that drifted

away from its original purpose. Negative emissions technologies must be developed with the scientists, customers and ecosystems in mind.

The current state of carbon capture

There is a critical need to innovate in the domain of carbon capture technologies. Even if we had a CDR technique that could sequester a megaton per year in 2020, it would have to double in capacity every year in order to reach a gigaton by 2030. But the challenge is more than scaling: as of the time of writing this, we do not have a leading technology that is both technologically mature enough to be ready for scaling and has favorable economics to do such scaling. Invention and human power is needed: In a capitalist society, the best way to generate broad interest in a topic is to demonstrate that there is money in it.

There are over three decades of work for scaling carbon sequestration, with public interest that varies with annual periodicity (Figure 2) in the Spring and Fall. There are approaches which aim to capture atmospheric CO_2 (ie, going from the ~400 parts per million (ppm), down to the preindustrial ~300ppm) and there are approaches that look to filter concentrated CO_2 out of industrial waste streams. While capture at the point of production is certainly important, the logistics of scaling such a technology to every industrial point source becomes unrealistic. The research in this paper biases away from industrial waste streams because the atmospheric capture (arguably) has a better chance of reaching the gigaton scale.

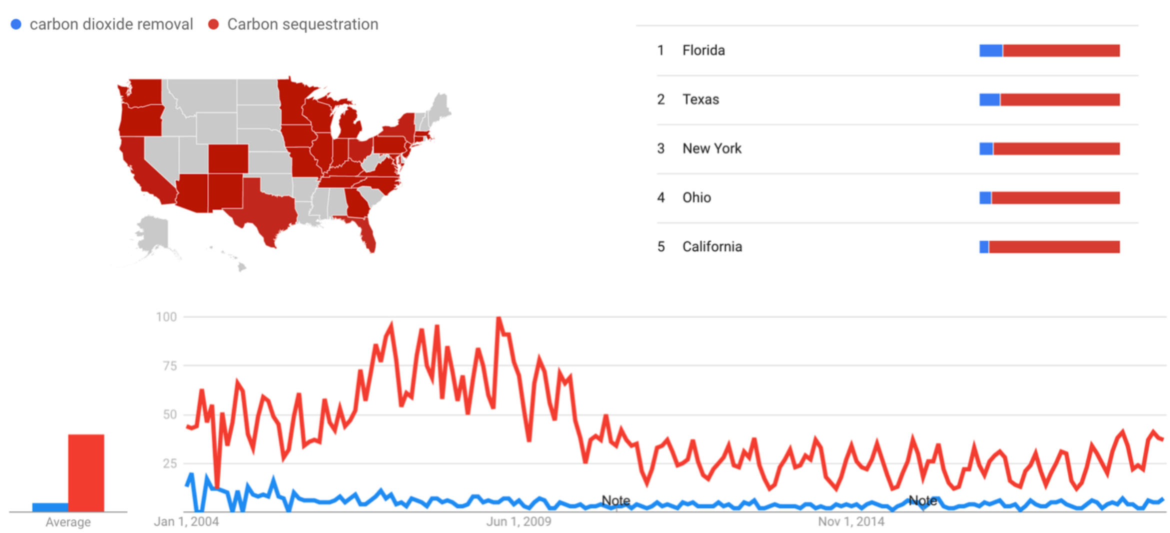

Figure 2 | Carbon Capture history according to Google Trends. Sequestration shows a periodic behavior with a 6 month period, peaking in April and November every year. The reason for the periodicity is unclear. Y-axis is a proprietary unit from google to indicate search volume. (Source: trends.google.com)

Existing technologies for carbon capture

"Carbon dioxide is not very reactive," Professor Betar Gallant explained in a press release (link) following the publication of her novel proof-of-concept battery that sequesters carbon during discharge (Khurram, He, and Gallant 2018), so "trying to find new reaction pathways is important." While the climate and ecosphere of the planet can be devastated by the atmospheric heating and ocean acidification of an additional 50ppm CO_2 in the atmosphere, from the physics perspective it is still a dilute gas that needs compression. So while such dispatches like Professor Gallant's from the cutting edge of chemistry are exciting and a critical foundation of the future NETs pipeline, they are still CDR approaches in early development with unknown scaling. Today, there are seven leading approaches for CDR of moderate maturity, including Direct Air Capture (DAC), Bioenergy with Carbon Capture and Storage (BECCS), and Ocean Alkalinity Enhancement. Because there are already many excellent overviews of existing CDR techniques (Mac Dowell et al. 2017; Hepburn et al. 2019; National Academies of Sciences, Engineering, and Medicine and Committee on Developing a Research Agenda for Carbon Dioxide Removal and Reliable Sequestration 2019), I will not attempt a redundant comprehensive overview of all approaches. To appreciate the industrial scale of the task, Figure 3 shows aerial views of the Archer Daniels Midland project in Illinois and the CarbFix project in Iceland, both variants of BECCs that are working towards, but not yet reached, megaton CO_2/year scale. The answer we are seeking is a CDR technique, or a pipeline of techniques, that have a feasible path to gigaton-scale sequestration that does not require government funding. We want to find profit in carbon capture.

Figure 3 | Existing Sequestration efforts. Left: The Archer Daniels Midland project can store roughly 1 million tons of CO2 per year in the Mt. Simon Sandstone, Illinois Basin, which has an estimated storage potential of over 250 million tons of CO2 per year (link). Right: The site of the CarbFix project in Iceland, which has buried 200 tons of CO2 by pumping carbonated water into basalt at $25/ton.

Not all carbon sequestration approaches necessarily yield usable byproducts. Figure 4 shows an illustrated table of CDR approaches , originally taken from the UNEP 2017 Emissions Gap Report (link), briefly annotated for their viability. Ocean Alkalinization, for example, describes a class of approaches where the pH of the ocean can be locally modulated with solutes in order to increase the CO_2 dissolution into the ocean. Because the ocean has a carbon storage capacity on the order of thousands of gigatons (Hepburn et al. 2019), it is an appealing resource in the race to develop carbon sequestration techniques. There are even arguments that such alkalinization could beneficial for certain ecosystems (Feng et al. 2016), but unfortunately the business challenge is akin to the "Tragedy of the Commons" in reverse. Just as individual actors are incentivized to maximally exploit a shared resource on the assumption that other players would do the same, those same actors could not expect a financial reward for altruistically restoring that shared resource. Similarly, enhanced weathering (Taylor et al. 2016) is an exciting direction, but with the challenge of potentially desirable scalability but without a clear method to recapture value. Reforestation and Wetland restoration have significant potential to sequester carbon, wetlands in particular are magnificent carbon sinks (Nahlik and Fennessy 2016), and have critical environmental benefits, but are better framed as government-supported projects. Until only recently, very few companies have been formed around CDR technologies that are ready for commercial growth (Table 2).

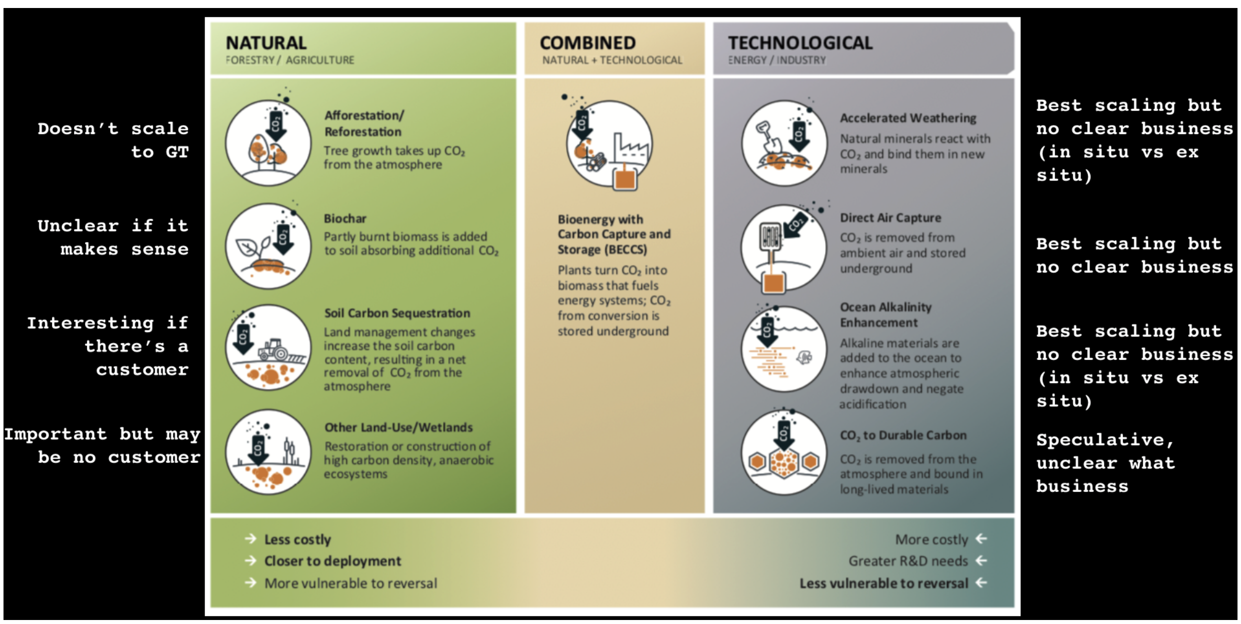

Figure 4 | Overview of CDR approaches. Using the graphic from UNEP 2017 Emissions Gap Report, we can

Only a subset of Carbon Dioxide Removal CDR techniques are able to produce cost estimates per ton of sequestered CO_2, and none have yet shown a concrete demonstration that, at the margin of a single ton sequestered, they produce more value than they consume. Figure 5, shows that the three leading techniques have varying confidence, ranging from Carbon Engineering and Climeworks' 10 years of operational experience to the Electro-Swing technology that was only just published. BECCS (Bioenergy with Carbon Capture and Storage) is a term that encompasses the utilization of biomass for energy via some combustion reaction, then permanently storing the carbon bioproducts somewhere, and a few pilot plants have broken ground in the past few years (Figure 3).

The most important number is \$100/ton, reported by David Keith and Carbon Engineering (Keith et al. 2018): besides being the lowest number yet reported in a peer reviewed publication, it is based on a decade of experience of, in David Keith's words in a lecture at MIT in November 2019: "nitty gritty, grind-it out, optimization of chemical engineering processes." \$100/ton is a cautiously optimistic number for atmospheric capture, and is an appropriate ballpark cost of carbon dioxide capture for exploring business opportunities.

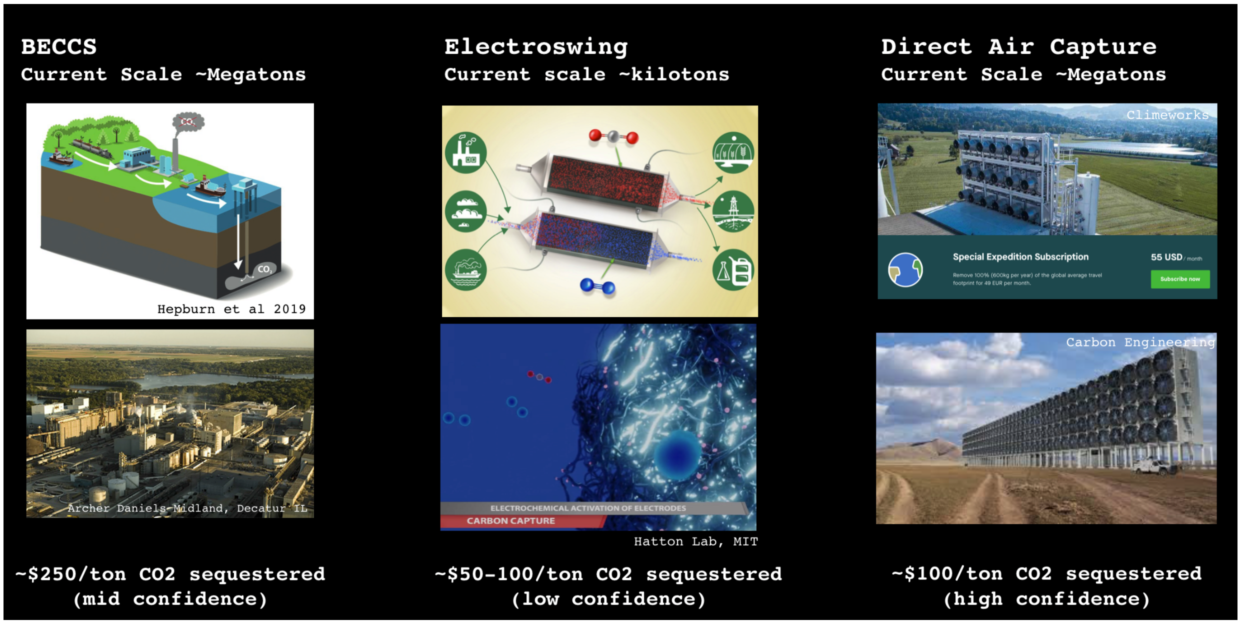

Figure 5 | Three CDR techniques with their respective cost estimates.

Existing businesses for capturing Carbon Dioxide

The heartbeat of a business is the delta between the costs and revenues. So if we use \$100/ton as a cost, what could the revenues be? Currently, there are few active markets for profitably sequestering carbon, the majority of which is some form of enhanced oil recovery (EOR) (Herzog 2018). In EOR, pure CO_2 is pumped into oil reservoirs in order to extract more oil from underground than would have been otherwise accessible, and as a lucky byproduct, the exogenous CO_2 is then trapped below the surface. At a \$20-40/ton value to the oil companies (Carbon Utilization Research Council, ClearPath Foundation 2018), EOR has been an important source of funding for the early decades of carbon capture, with notable contracts with Carbon Engineering, Global Thermostat and others, but for NETs to scale into the gigaton range, future markets must be created.

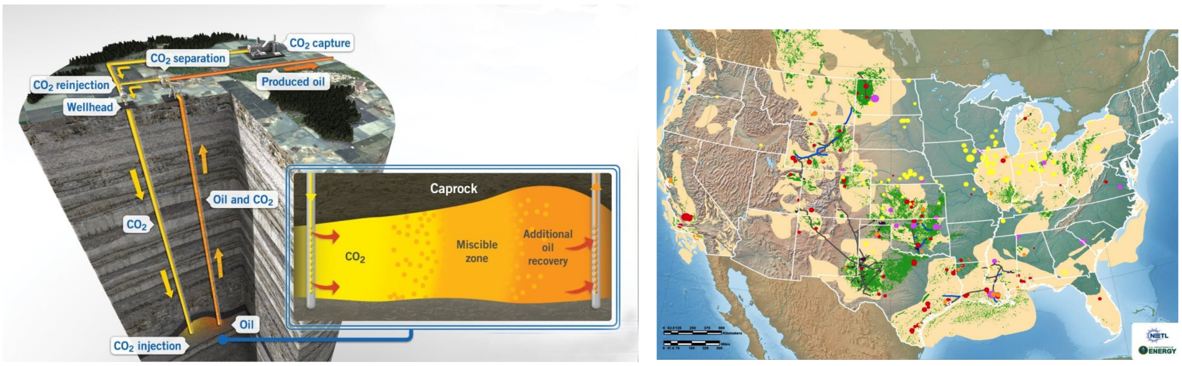

Figure 6 | Overview of EOR for a CCUS plant (left), and a map of the US highlighting opportunities for rapid large-scale carbon management in U.S. heavy industry (right). The green fields represent oil fields suitable for EOR, while the beige zones represent saline formations that may serve as storage sites. Yellow circles = ethanol plants, orange circles = refineries, purple circles = chemical plants, and red circles = petroleum operations. Black lines represent existing CO2 pipelines, and blue lines represent proposed extensions. Sources: (Carbon Utilization Research Council, ClearPath Foundation 2018), and (Energy Futures Initiative 2018)

If the value of CO_2 to EOR is $20-40/ton, but DAC is on the order of $100/ton, how can that make good business? The answer is either combining DAC with subsidies (at the 45Q tax credit effectively brings DAC to breakeven), or capturing from concentrated point sources. To explore if we could do better than $100/ton, we can see from physical first principles that the energy required to concentrate and compress atmospheric CO_2 is ~30kJ/mol, and assuming a 35% efficiency, a practical limit of 90kJ/mol (MacKay 2008). Dr. Adam Marblestone does an excellent exploration of the physical considerations in his second of three blog posts on this topic. Speaking very roughly, this could map to about $30/ton as a practical cost floor of sequestered atmospheric carbon. In some cases, a portion of the work of concentrating the CO_2 has already been done. The Energy Futures Initiative 2018 report did an analysis of point source pollution capture, recreated below in Figure 6, showing that there are some specific situations in which the cost of sequestering the carbon is likely to be less than the value it produces. However, there are more dimensions to consider than just cost.

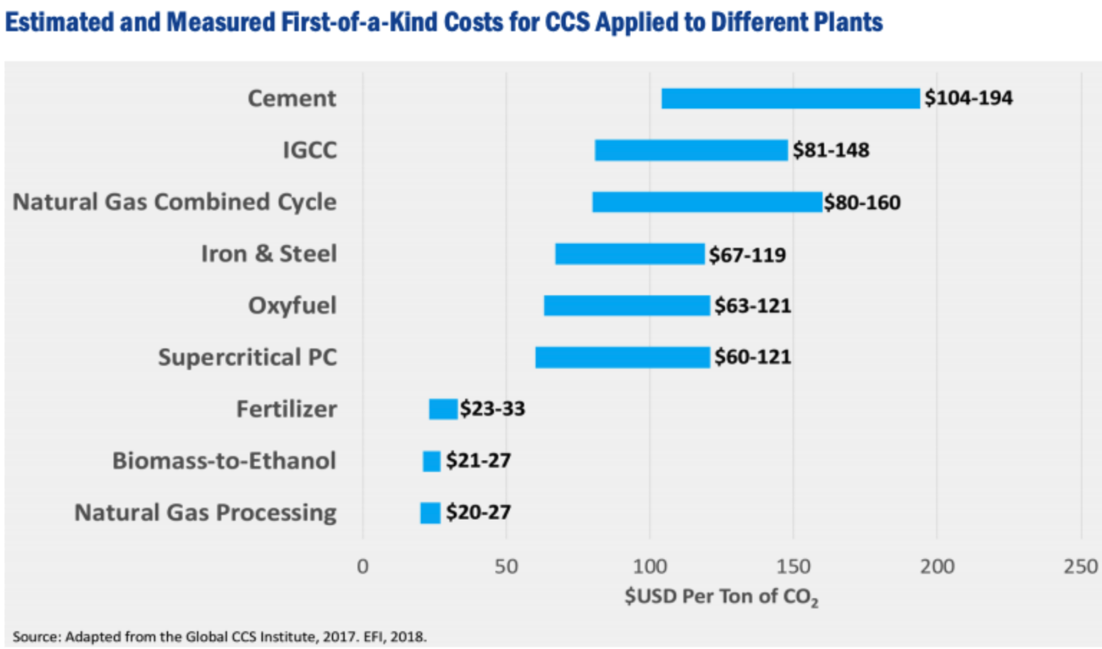

Figure 6 | Carbon capture from industrial waste is not necessarily cheaper than direct from the atmosphere (Energy Futures Initiative 2018)

For an excellent overview of the economic projections for known markets, I advise the reader to consult (Hepburn et al. 2019). The capstone figure has been copied below for reference, it shows the many dimensions to considering carbon capture at scale: storage duration, profitability, technology readiness level (TRL) and mass of carbon per sector. For example, polyol is highly profitable but a very small in potential gigatons of CO_2, whereas methane is both large (>2 Gt CO_2) but marginally very expensive at $500/ton CO_2 utilized. In the subsequent sections, I will do a similar analysis but reverse engineering from the products which could be sold in present and future markets.

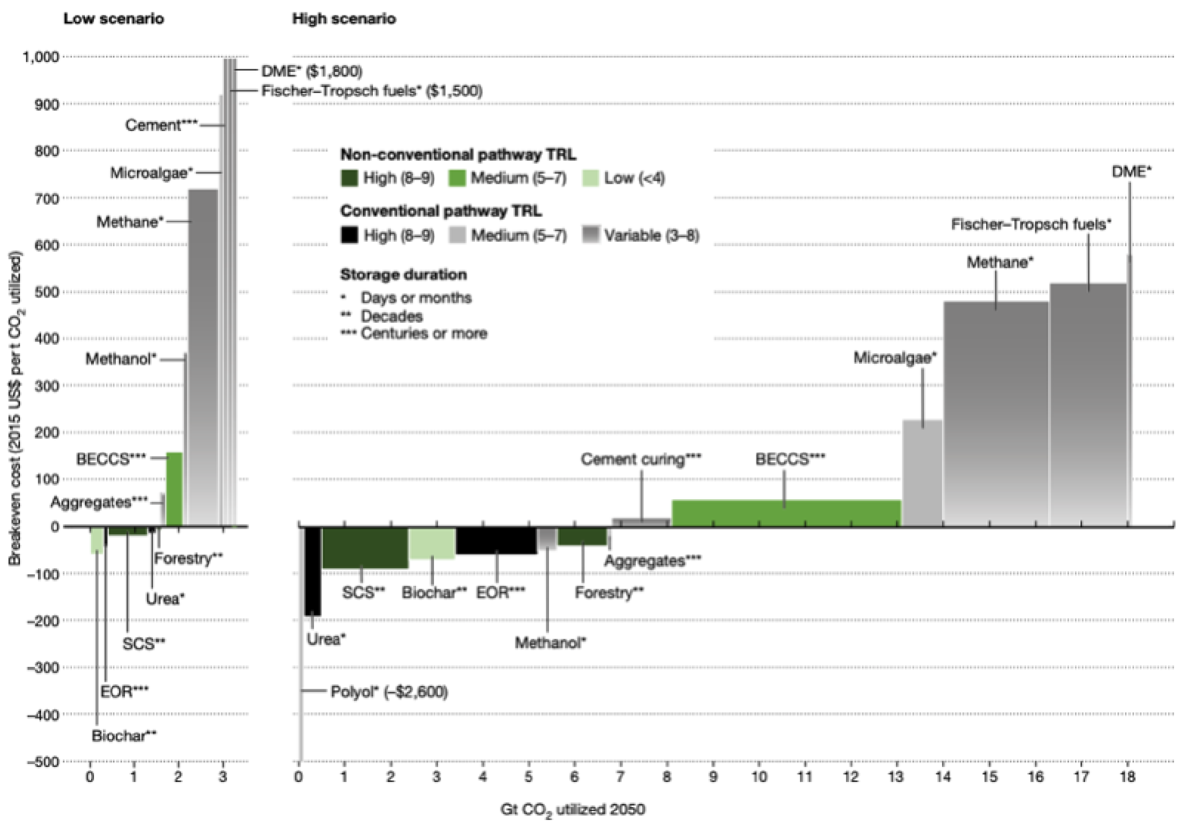

Figure 7 | Summary of marginal economics. This figure from Hepburn et al 2019 is an excellent overview of the marginal economics of carbon capture and utilization strategies. The Y-axis of this plot is the breakeven cost of the existing technology: a negative breakeven cost means the strategy is already profitable, and a positive value would mean subsidies would need to come from somewhere in order for that utilization pathway to be sustainable. The X-axis is the capacity, in gigatons of each one of these outputs.

Future markets of carbon capture products

In 2004, the DOE did a survey of the “Top Value Added Chemicals from Biomass,” a report which identified 12 high value products that could be produced with biology rather than GHG-producing chemical pathways (G Petersen 2004). That paper was downloaded over 170,000 times, and catalyzed research and commercial activity on the order of hundreds of millions of dollars over the subsequent 10 years (link). Producing a similar contribution for the domain of negative emission technology would be a step towards the gigaton goal.

Searching for viable business opportunities has many known and successful strategies, such as Steve Blank’s Business Model Canvas and YCombinator’s Startup Class. The classic starting approach for the aspiring entrepreneur is to search for a large and fragmented market: such a market has potential both for allowing new entrants and future consolidation by a dominant player that introduces a new technology. Energy and ammonia production are two candidates that satisfy such initial constraints, and both markets are gigaton consumers and producers of greenhouse gasses (Kätelhön et al. 2019). The other attractive business opportunity is in markets which are niche and growing, such as the use of carbonates in building materials. Finally, there are new markets which transformative technologies could create, such as carbon nanomaterials. Table 1 is a summary of markets that could be relevant to carbon capture technologies.

What	Pro	Con	Price per ton	Scale
Hydrogen (H_2)	The most energy dense fuel on the planet (by mass). Can be produced either by renewable energy or bioproducts of CDR (Rau, Willauer, and Ren 2018)	Energy would need to be made in a central facility (MacKay 2008). Storage is hard	~$500/ton H2 (source)	Large
Pure CO_2	Currently used as an input for enhanced oil recovery (EOR), greenhouses and plastic manufacturing (Hepburn et al. 2019)	Requires relationship with the customer not to release the CO_2 back into the atmosphere	$20-40/ton CO2 (source)	small
Ammonia (NH_3)	Currently the most CO_2 intensive chemical to produce (1% GHG, source). NH_3 can also be used in a fuel cell.	While the Manthiram Lab at MIT has shown CDR+ammonia production, scale is unknown. Old Market	$500/ton (source)	medium
Carbonates	Can be used as building materials, generating $ and offsetting concrete.	Requires an industry to develop + validate what materials	$25-$50 per ton (source)	Large
Carbon Monoxide	Hub molecule for much chemical manufacturing	Very poisonous, difficult to store and transport.	$600/ton (source)	medium
Pure water	(Mankin et al. 2019)	Little technical work on the topic so far	Varies by geography	Large
Consumer Products	Recent 5 years have shown many new companies based on technologies. Notably, algaes are now recognized as a crop	Very fragmented market in production	Varies. See list of companies in Table 2	small
Heating/Cooling	24.6% of global emissions, so the biggest single category according to Project DrawDown	No known work for carbon-negative HVAC	no	Large
Soil Nutrients	Soil is abundant and hurting for carbon.	Agricultural markets are extremely risk averse and cost sensitive	$400/ton, ~$100/acre (source)	Large
Specialty Materials	Carbon Nanotubes (Licht 2017) Commercial biopolymers growing ~15-20% annually (source)	Very broad topic. Not necessarily sequestration.	Carbon Fiber $25k/ton (source)	Small

Table 1 | Summary of viable commercial products from sequestered carbon. What differs from this table as from other similar surveys is that speculative outputs such as high value materials and heating/cooling are suggested.

A notable absence in Table 1 is fuels. Combining Hydrogen gas with sequestered CO_2 can produce combustible fuels, which then have market value. Carbon Engineering has started doing this with their DAC system, as is the younger Prometheus Fuels, which has announced partnerships in the high performance aircraft market (see this news release). The CEO of Prometheus Fuels posted on LaunchHN: “We’re not the first to make fuel from the air - in fact Google, Audi, Carbon Engineering, Global Thermostat, Climeworks, and labs at universities and national labs have all done it before us. What no one has been able to do so far is to do it at a low enough cost to compete with fossil fuel.” As air travel is such an extreme producer of CO_2, offsetting the traditional jet fuel can be a significant net reduction. However, because the final product is carbon that is designed to be re-released into the atmosphere, and so net carbon neutral, I am not considering fuels in this paper. However, for those curious, the estimated value of captured CO2 turned into fuel is $120/ton (calculated using the $50/barrel price floor of oil and the fact that one gallon of gasoline produces twenty pounds of CO_2) . Prometheus Fuels and other companies are still listed in Table 2, which is a list of known companies who produce commercial value from carbon capture.

Exploring 4 opportunities for profitable CO2 capture

Reviewing Table 1, I chose four specific product categories to explore in greater detail: Hydrogen, construction materials, high margin materials and soil recarbonization. For each subtopic, I give a brief and subjective business ranking from 1-10 (1=worst, 10=best) on aspects of the business, then explore the pros and cons of each direction of potential future businesses.

Carbon-Negative Hydrogen

Technology Readiness: 4 (interesting but speculative work)
Market readiness: 5 (MW industrial scale)
Market attractiveness: 2 (very price competitive)
Market size: 6 (large but competitive)

Hydrogen power is an old idea that has never quite taken off. Per mass, it is the highest energy density of any fuel, and the combustion of hydrogen produces only water as waste. Why has this miracle fuel never scaled? The reason is that Hydrogen cannot compete with gasoline for practicality (H_2 is difficult to store and transport) and consumer cost in distributed use cases such as cars (MacKay 2008). However, in concentrated production facilities, H_2 can be comparable to solar in terms of kWh per square meter when produced by algae, or H_2 can be produced by electrolysis powered by renewable sources. Could this foundation, coupled with many recent innovations, create modern markets for Hydrogen?

One of the most scalable proposed NETs is electrogeochemistry, which can produce Hydrogen as a byproduct and has a theoretical scaling to over 100 gigatons per year (Rau, Willauer, and Ren 2018). YCombinator did a nice writeup of these ideas here. The core idea is that combining electricity, saltwater, minerals and carbon dioxide can produce carbonates and H_2 gas. The carbonates will sequester carbon while the H_2 can be utilized. Figure 9 shows one of the proposed chemical pathways and that the authors project the scale of this production could be orders of magnitude larger than any other form of CDR. Assuming these projections to be accurate, it then needs to be explored if gigatons of H_2 have plausible business prospects.

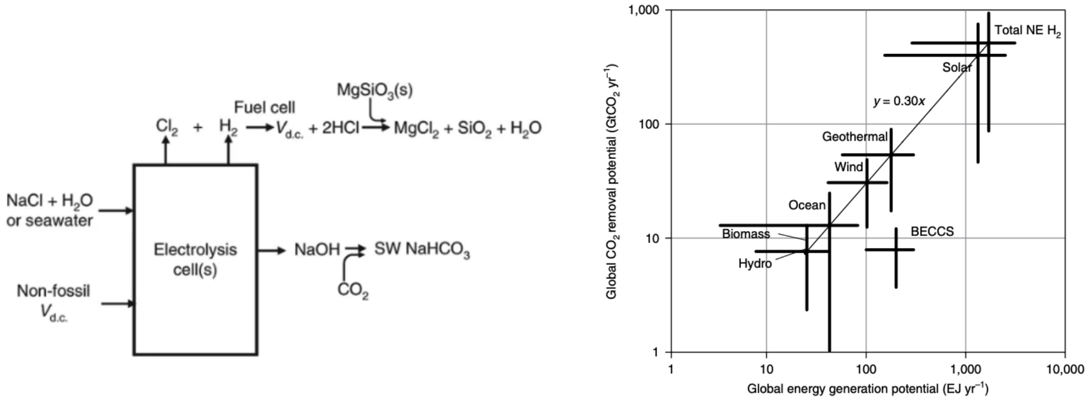

Figure 8 | Shown left is a conceptual chemical reaction outlined in (Rau, Willauer, and Ren 2018) showing how renewable electricity and saltwater can produce hydrogen.

Hydrogen is valuable not only as a power source, but also as a commercial feedstock to valuable commodities such as ammonia (Figure 9). Hydrogen power seems compelling because many of the power plant components (such as turbines) can be theoretically repurposed from natural gas plants. Furthermore, H_2 can be mixed with natural gas for hybrid operation. In addition to power, the Steam-Methane Reforming process that currently produces industrial H_2, say for ammonia production, is a large source of GHGs (ammonia production in total is 1% of the global GHG), so the production of hydrogen at first appears to be an exciting business opportunity. However, globally there have been very few completed hydrogen power plants: I was only able to find a handful of examples that actually made it to operation. There must be a reason for Hydrogen's underperformance.

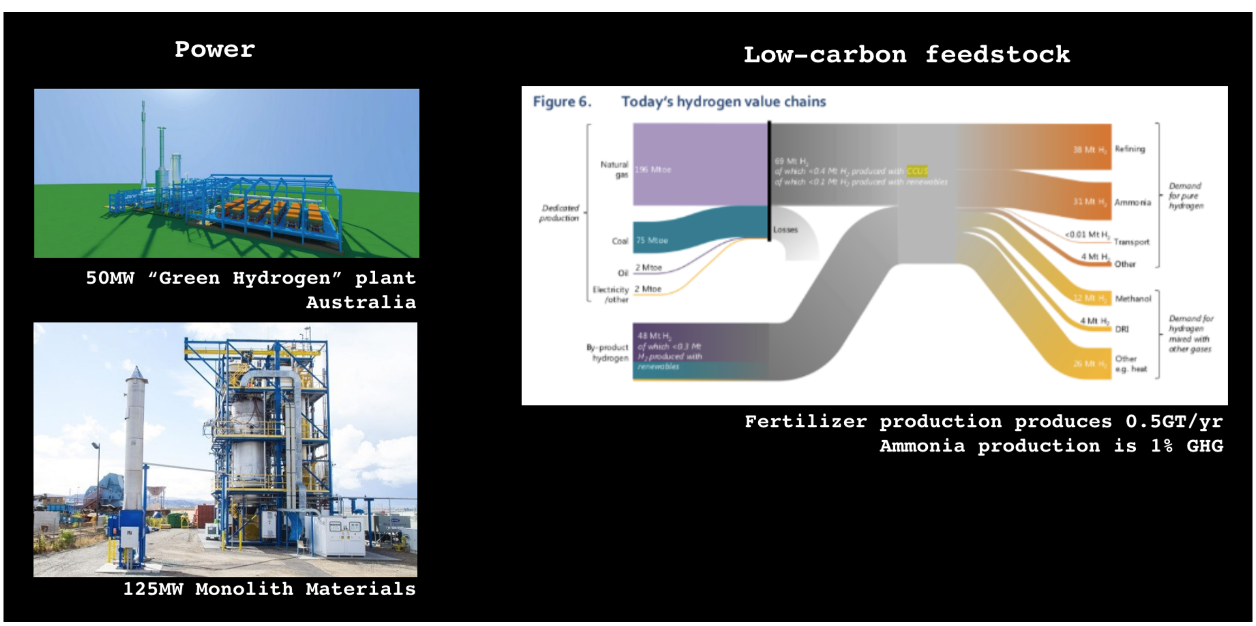

Figure 9 | Use cases of Hydrogen. For power, two examples of Hydrogen Power plants, a 15MW plant from Australia (link) and a 125 MW plant in Nebraska (link). For chemical processes, ammonia and fertilizer require H2 in production. Right figure taken from (IEA 2019)

The limitations on hydrogen depend on a few challenges. First, the production of hydrogen via electrolysis has been limited by expensive rare metal catalysts, although there have been fascinating developments in recent months (Vogt et al. 2019; King et al. 2019). Synthetic biology has also been making progress towards better hydrogen production (Rao et al. 2019; Liu et al. 2016) via microbes, and NREL has an active research initiative in this direction (link). Until those new methods reach scale, power from hydrogen will remain ~5 times more expensive than coal (IEA 2019). Secondly, using hydrogen as a power source requires competing against nuclear and solar. Figure 10 is a plot from Francis O' Sullivan's lecture (link) that shows the nature of the energy market, and that there is an effective queue of energy utilization by price, meaning H_2 energy could be produced but never purchased if it's more expensive than solar. Given that the competitive prices go below zero, it shows that Hydrogen would be an extremely low margin business at best. At worst, it would distract funds from nuclear milestones (breakeven fusion power, for example), which would be a much higher impact contribution for humanity than Hydrogen power.

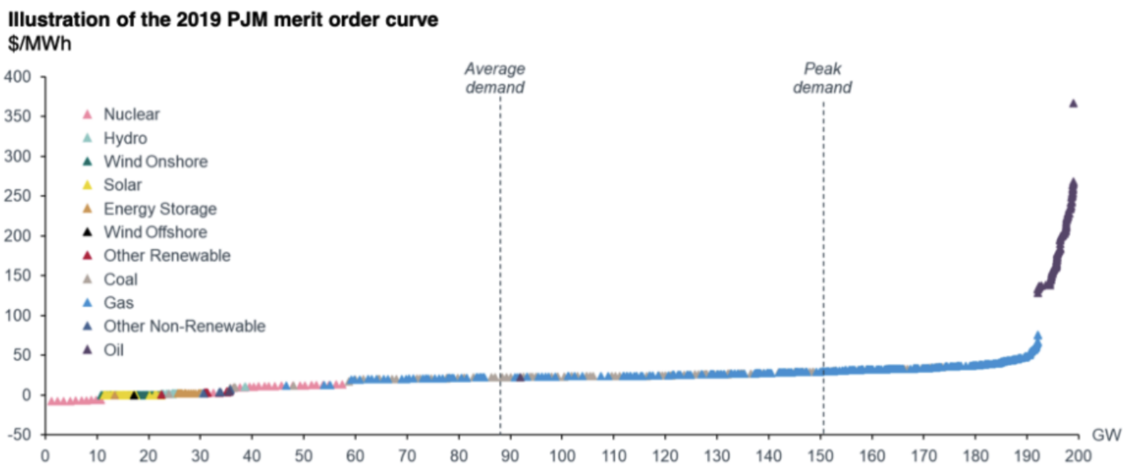

Figure 10 | Hydrogen has the potential to be both carbon-negative in production. However, the commercial value of hydrogen as a power source is a function of the state of the power market. On the right is a plot from Francis O'Sullivan (link) showing the priority queue of power sources, showing that negative prices for power exist on most modern grids at any given time.

For the vision of gigaton-scale electrogeochemistry to become a reality, the hydrogen economy would need to be built on an ocean economy to satisfy the requirements of saltwater. Floating machines, or even cities, on the ocean, powering themselves with solar panels and hydrogen fuel cells, is certainly a wonderful vision, but it is unclear if this is the most direct path to gigaton sequestration.

Building Materials from Sequestered Carbon

Technology Readiness: 7 (technologies seemingly working at kT-MT scale)
Market readiness: 10 (there is already a huge market)
Market attractiveness: 2 (extremely price sensitive, low margin)
Market size: 10 (unbounded)

Sequestering carbon dioxide into carbonate solids is the most active, non-EOR carbon capture market. There has been at least $50MM of venture dollars invested to date, and given that construction is a trillion dollar market, it is likely that such investments will continue.

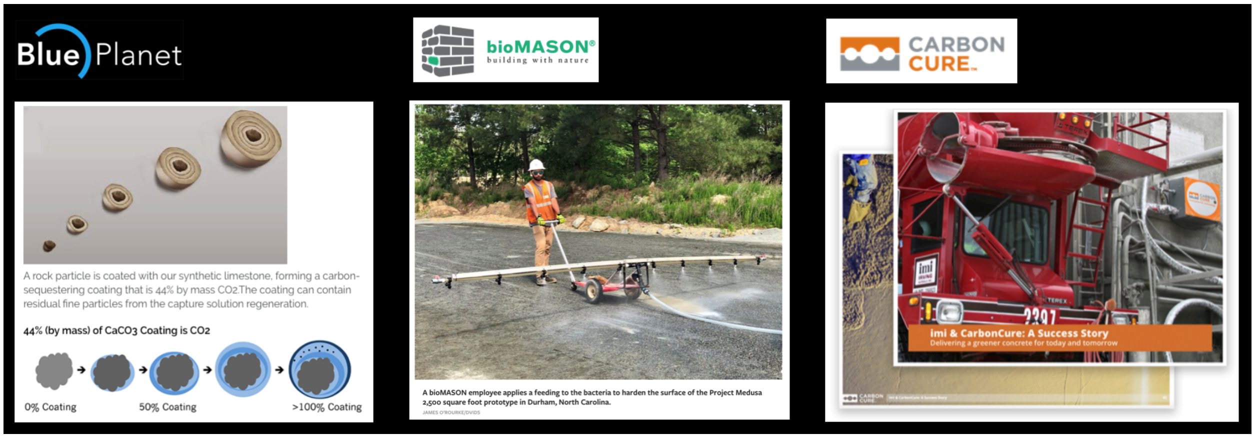

Figure 11 | Three exemplar startups combining CCS and construction materials

Creating carbon-negative building materials can take several forms varying in its integration with carbon capture. One end of the spectrum, the company could assume that there will be abundant sources of pure CO_2 from carbon capture techniques, and utilize various sources agnostically in the production of materials. Carbon Cure uses pure CO_2 to cure concrete faster and harder than existing techniques that are carbon intensive, and has recently gained the support of Bill Gates (link). While Carbon Cure's strength is closely integrating with known processes, Blue Planet aims to create a building material with a radically different approach. Using a stream of pure CO_2 and a starter set of minerals, they aim to produce "geomass" by creating a synthetic limestone of hard mineral composite, that is 44% calcium carbonate. Still in its early days with about $1MM in investment, Blue Planet's technology was used to produce a small portion of SFO airport's tarmac.

On the other end of the spectrum, building materials could both capture and sequester the carbon. For example, microbes could create capture the carbon dioxide and produce the carbonates. Popular Mechanics explains the process of BioMASON (link): "Blue Horizons [a think tank within the Air Force] is working with BioMASON, a North Carolina biomanufacturing company that's developed a technique for turning sand and soil into durable, hard surfaces. Engineers pour sand into brick molds and add bacteria to the mix. Nutrient-rich water is added to feed the bacteria and allow it to grow. The bacteria creates calcium carbonate crystals that bind the sand grains together, resulting in a durable brick that can be used in construction."

What's appealing about this domain of business is it's a huge market with many possible entry points. What's bad about this market is that it's ultimately a very low margin business: concrete sells at $25-50/ton ("Building a New Carbon Economy: An Innovation Plan," n.d.) concerningly close to the lowest cost estimates of carbon capture. In addition, large sales forces would be necessary to close the biggest deals, which would further erode at profitability. That said, it will be of high interest to the global community to see these companies scale, as a few successful exits would certainly garner more innovation and investment in the carbon-negative construction industry. In response to this low margin, high volume industry, it is also worth considering what the opposite market could look like: what are high margin, low volume markets?

High-margin materials

Technology Readiness: 3 (it is primarily speculation or concept papers)
Market readiness: 3 (there are small niche markets)
Market attractiveness: 10 (high profitability)
Market size: 4 (small now but potential for rapid growth)

One of the greatest things Elon Musk has done as an entrepreneur is to set Tesla's goals beyond simply being the best electric car, but rather to become the best overall car. With this concept in mind, it feels short-sighted to consider how cutting edge technology could be used to produce centuries-old materials such as concrete. Just as the Tesla Model S won the MotorTrend "Car of the Year in 2013," how might the process of carbon capture produce some of the most valuable materials that could dramatically outcompete incumbents?

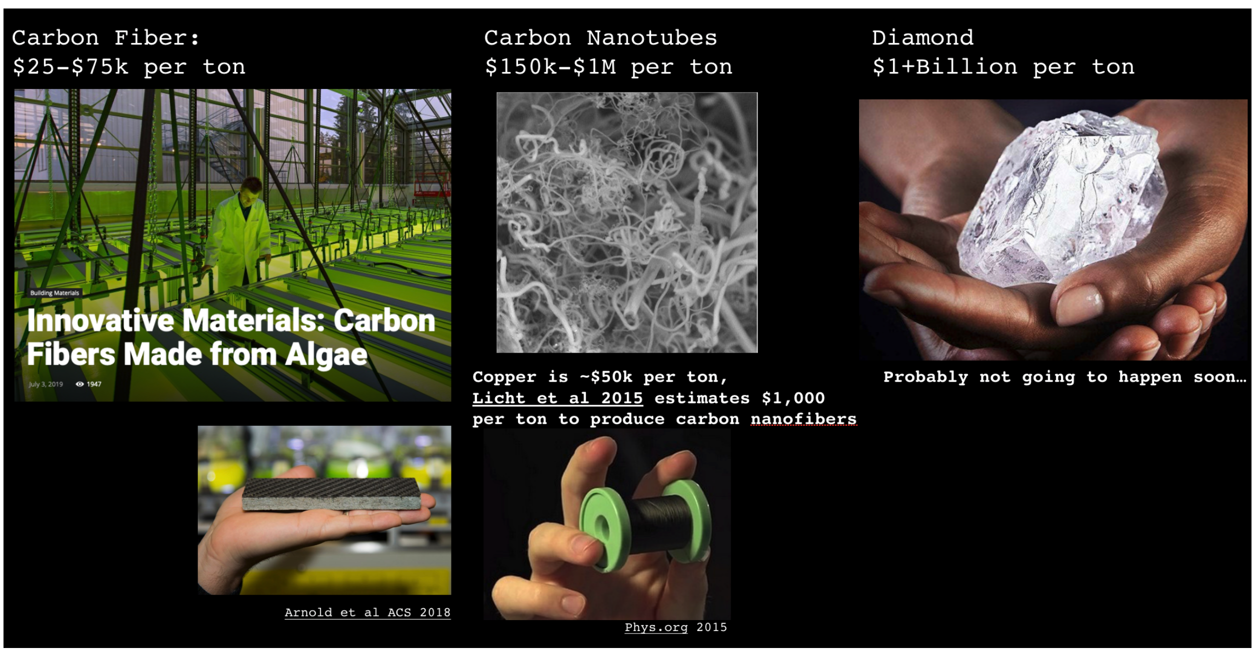

Figure 12 | Speculative markets for ultra high value materials that could be produced via CCS.

High value materials such as carbon fiber represent an exciting opportunity. At an extraordinary price of ranging from $25k up to $75k per ton for aircraft grade (link), the ultra light, ultra strong material has become a symbol of quality for mountain bikes, prosthetic limbs and sportscars. Profesor Thomas Brück and colleagues from the Technical University of Munich recently completed a technical and economical study of the production of carbon fiber from algal biomass (Arnold et al. 2018). Specifically, the authors identify an essential precursor to carbon fiber, polyacrylonitrile, that can be developed from microalgae-derived lipids. This work is particularly interesting because they model the economics of the carbon fiber production all the way into the gigaton range, concluding that “process combinations with algal biodiesel-production and biomass-liquefaction components come close to meeting the multiple constraints and justify progressing to extended research and development activities.” With proof of concept carbon fiber already in hand (Figure 12, bottom left), carbon fiber and similar high performance carbon-based materials are an important direction for consideration.

Carbon nanotubes (CNT) have been long lauded to bring forward a new era of technology. Their tiny footprint, biological compatibility, electrical properties and mechanical properties have generated over a decade of interest. While the hypothesized markets for electronics has so far failed to materialize, there are still promising applications in industrial processing such as water filtration (McGinnis et al. 2018). In an ACS article (link) provocatively titled “Diamonds from the Sky”, Professor Stuart Licht claimed that his lab developed a technology that could produce carbon nanofibers from CO2, a $10,000 product for $1,000 cost of CDR (Licht 2017). The research has been commercialized into a startup, C2CNT, which is a finalist in the prestigious NRG Cosia Carbon XPRIZE. Little information is otherwise known about the company aside from an investor group acquiring an equity stake in the early stage company (link), so C2CNT was not included in Table 2.

A third option of high-margin carbon capture is biological work. Enzymes are protein machines that can do a variety of atomic-scale tasks: cleaving DNA, building polymers, catalyzing reactions and mass producing chemicals of interest. Because of the nitrogen content, it’s unlikely that proteins themselves could ever be a form of gigaton-scale sequestration. However, it is feasible that systems could be engineered to do some task, recycle biological materials of dead biomass of the living machines and sequester carbon from each lifecycle in recalcitrant carbohydrates In the case of a company called Solugen, which has raised $55MM to date, they have built a business using biology to replace GHG-producing chemical processes. “The revolution is the commoditization of biomanufacturing, specifically enzyme production,” Chakrabarti says. “Instead of our enzymes costing $1,000 per kg… It’s $1 to $10 per kg” (link). Similarly, LanzaTech, now a large company with $250MM of investment and 14 years of experience, uses microbes to recycle carbon-based materials into ethanol and other products.

Recarbonizing the soil

Technology Readiness: 8 (many biological tools)
Market readiness: 5 (wary of new technology until proven)
Market attractiveness: 6 (litigious and unpopular large corporations)
Market size: 10 (unbounded)

Global decarbonization of the topsoil stands out number one as both a critical problem and an enormous resource for carbon sequestration. It is one of humanity’s greatest challenges that the medium on which we grow our food on has a predicted expiration date. Although the headlines saying “Only 60 harvests left” may have been alarmist (link, opposing link), it is established that the soil health is deteriorating rapidly and unsustainably. The soil is also one of humanity’s greatest hopes to scalable sequestration, as the soil has the capacity to sequester 5-12 gigatons of CO_2 per year (Lal et al. 2018). Just a 0.4% increase of carbon in the soil can yield 2-3 gigatons of carbon sequestration, hence the “Soil Carbon 4 per thousand” initiative (link) (Minasny et al. 2017). Furthermore, the confluence of modern techniques in both high throughput, high precision synthetic biology and data science make soil recarbonization one of our most actionable goals.

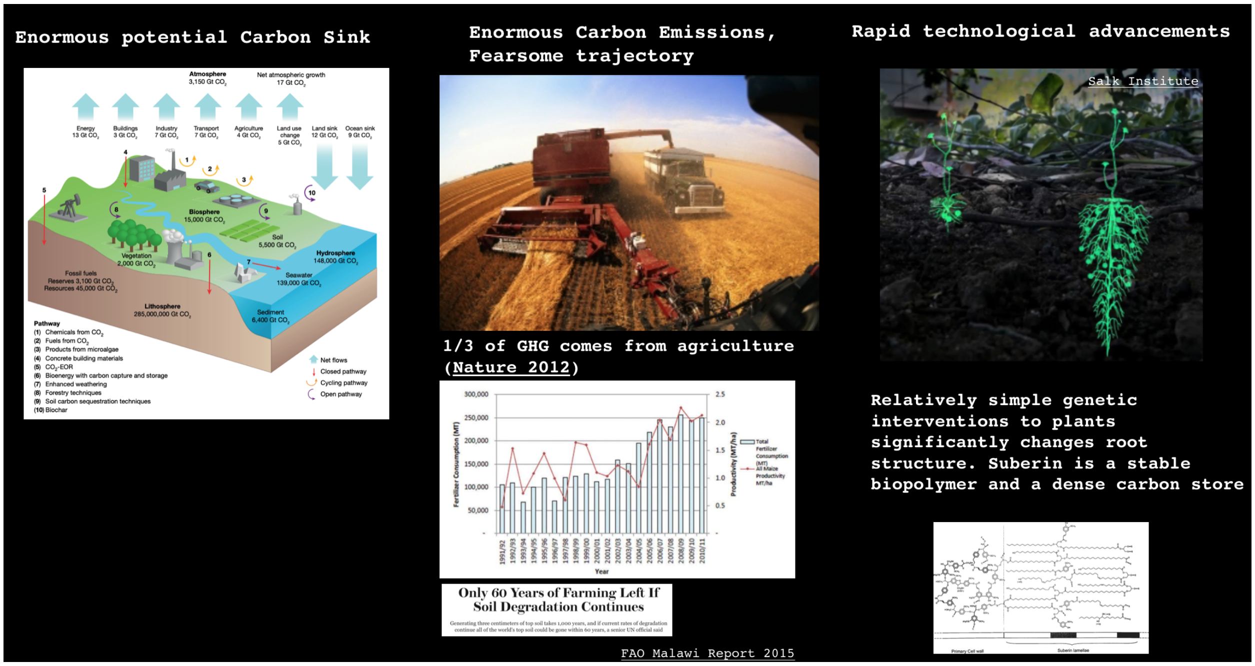

Figure 13 | The three foundations of soil recarbonization as one of the best opportunities for gigaton carbon capture. It is known that the soil represents abundant storage capacity for sequestered carbon, at least on the order of decades (left). Middle: current agricultural practices are known to be unsustainable. Right: Professor Joanne Chory's work at the Salk Institute demonstrate the ability to modulate plant root systems

The cause of the decarbonized soil problem is entirely human caused and could certainly be human repaired. The overuse of fertilizers and disruption of natural soil ecosystems via mechanical disruption (ie, tilling) are the results of a heavily consolidated corporate farming industry. Monocrop agriculture, abandonment of sustainable practices such as crop rotation and removal of cover crops also contribute to a dearth of natural carbon that used to exist in the soil in the form of microbes, decomposing plant matter and carbohydrates. Overuse of fertilizer has created infertile soils and made farmers dependent on more fertilizer: the center-bottom plot in Figure 13 shows a plot from the FAO Malawi 2015 report that shows the increasing correlation of fertilizer use to maize productivity. So, in addition to reducing the footprint of an already unsustainable industry -- a third of global GHG emissions are produced by agriculture (Gilbert 2012)-- and protecting the food security of many countries, recarbonizing the soils are also an attractive method to carbon sequestration.

Using public farming number in Illinois for 2017 and 2018 (link), we can estimate the cost of fertilizer to be on the order of $400/ton. This gives a comfortable operating margin from the ~$100/ton estimate of capturing CO_2 to then be converted into useful material for enriching the soil. Furthermore, the carbon can be sequestered right at the point of capture, which has advantages over other approaches like DAC which may require CO_2 transport. However, agriculture as a market is challenging due to the understandable hesitancy of the customers (farmers) to try anything unproven given that a single bad harvest can bring them financial ruin. To date, there have been two specific case studies showing exciting results with agricultural innovations for carbon capture.

Professor Joanne Chory and her group at the Salk have demonstrated the ability to modulate plant root size via microRNA interventions. The power of such a technology is that the root systems produce suberin, a carbohydrate with a long lifespan inside the soil as if it is decomposed by an organism, that organism will also stay in the soil. The increased biomass in the soil from the overall root system is then hypothesized to improve the soil health. Although it's to-be-determined if her team's modified plants will become a self-sustaining entity outside of the lab, a recent $30MM grant from the TED foundation (link) and an excellent set of collaborators sets the expectations high for this project, titled Ideal Plants (link). It has recently also been shown that a for profit company can be positioned to sequester a gigaton of carbon profitably.

Indigo Agriculture started with an insight that a microbial coating for seeds would promote greater plant productivity via symbiosis, and has grown into a company with a billion dollar revenue in under five years. In doing so, Indigo has demonstrated that new techniques from the synthetic biology field can be applicable at a national scale and that microbiology's integration with sensor technology creates closed-loop systems that can outcompete traditional fertilizer. In 2019, Indigo launched the Terraton Initiative, a plan which leverages Indigo's multi-faceted contact with farmers to eventually pay farmers $15-20 for every ton of carbon they leave in the ground (link). Such an initiative is not charity, it could only be offered from a corporation if they were confident in their net gain from such an initiative. Such initiatives also promote fundamental research and promote entrepreneurship in a plant microbiology.

Nitrogen fixation, the process by which nitrogen, crucial to plant life, can be integrated from the atmosphere into an accessible format, has long been an engineering goal of plant biologists. In the past few years, there have been significant advances in plants that could fix their own nutrients, obviating the need for fertilizer and possibly being robust against depleted soils (Temme, Zhao, and Voigt 2012; Bhardwaj et al. 2014). Pivot Bio is one such example: by developing a novel symbiotic relationship between plants and a nitrogen fixing microbe, the need for fertilization is greatly decreased. With $86MM in funding, such a company, which could have been previously considered "just" a farming technology, could soon be viewed as an integral component to a carbon capture ecosystem.

Table of CDR companies and funders

Many companies have been mentioned in this piece, and a collection of all companies that are specifically built around carbon capture are enumerated in Table 2. Similarly, a short list of relevant investors are enumerated in Table 3.

Company	Website	Year Founded	Carbon Capture	Valuable output	Latest Funding
Carbon Engineering	https://carbonengineering.com/	2009	DAC using liquid sorbent	EOR, Fuels	$70MM

Climeworks	https://www.climeworks.com/	2009	DAC using solid sorbent	EOR, consumer offsets	$30MM
Global Thermostat	https://globalthermostat.com/	2010	DAC	EOR, CO2	$20MM investment
Prometheus Fuels (Fuel from the air via carbon nanotubes)	https://www.prometheusfuels.com/	2019	DAC using liquid electrolyte	Alcohol upconverted to jet fuel via CNT	$150k
Carbon Cure (CO_2 cures cement)	https://www.carboncure.com/	2007	agnostic	Cured Cement	$9.3MM
Blue Planet (mineralization building material)	http://www.blueplanet-ltd.com/	2012	agnostic	44% CO2 rocks for building	$1MM
Hy-Tek Bio (algae in flue gas)	http://www.hytekbio.com/	2009	algae in flue gas	palm oil and other bio products	<$1MM in grants
Biomason	https://biomason.com/	2012	microbes	bricks	$9.9MM
LanzaTech	https://www.lanzatech.com/	2004	agnostic	fuels and chemicals	$250MM
Industrial Microbes	http://www.imicrobes.com/	2014	microbes	Manufacturing industrial chemicals	$1MM SBIR in 10/2019
Opus12	https://www.opus-12.com/	2018	Point source carbon capture	Fuels and chemicals	$1MM SBIR in 10/2019
Kiverdi	https://www.kiverdi.com/	2008	Microbes	protein, plastic, soil	Unpublished
Oakbio	https://www.oakbio.com/	2008	agnostic	protein (as NovoNutrients), plastic, soil	~$100k grants
NovoNutrients (OakBio alias)	https://www.novonutrients.com/	2009	agnostic	fish feed protein	~$1MM
Carbicrete	http://carbicrete.com	2016	agnostic	Concrete	$2.1MM
Solidia	https://www.solidiatech.com/	2008	agnostic	Concrete	$27MM
Solugen	https://www.solugentech.com/	2016	agnostic	Hydrogen Peroxide	$55.2MM

Table 2 | Collection of for profit carbon capture companies

Firm Name	Website	Notable Deals
Ultra Capital	https://www.ultracapital.com/	Funds energy projects, not companies
Breakthrough Energy Ventures	http://www.b-t.energy/ventures/	PivotBio
Acorn Innovestments	http://acorninnovestments.com/	Biomason
Y Combinator	http://carbon.ycombinator.com/	None yet
Cyclotron Road	https://www.cyclotronroad.org	Opus12
Novo Holdings	https://www.novoholdings.dk	Lanzatech
Fifty Years	https://www.fifty.vc	Solugen
IndieBio	https://indiebio.co/	OakBio
Sean O Sullivan Ventures	https://sosv.com/	Novo Nutrients
Unreasonable Group	https://unreasonablegroup.com/	Kiverdi
InnovoBot	https://www.innovobot.com	Carbicrete
NRG COSIA Carbon XPRIZE	https://carbon.xprize.org/prizes/carbon	C2CNT, Carbon Cure

Table 3 | Table of relevant investors with example investments in CCS.

Conclusion

Solving the climate problem is one of the greatest challenges of our lifetimes. It is essential that we frame this battle positively and develop stories of successful efforts to combat our changing climate. It's possible that negative emissions technologies could be one of the first opportunities to show tangible results from the efforts to a larger audience. That is, perhaps showing people a block of carbon pulled from the sky is enough to say that we do have a chance to win this effort against global inertia that was two centuries in the making. Perhaps this could inspire people that it is worth making the personal decisions to drive less, eat less beef and urge their elected officials to promote climate-friendly policies. If we've learned anything from the exponential computer science growth of the past decade, it's that entrepreneurial activity can be a magnet for people of diverse backgrounds. So I urge us to appreciate the value of both angles of a large problem: the top-down approach of reverse engineering from 2100 (ie, considering a global optimality balance of approaches, (Belaia 2019)), and a bottom-up approach of starting one pound of CO_2 at a time.

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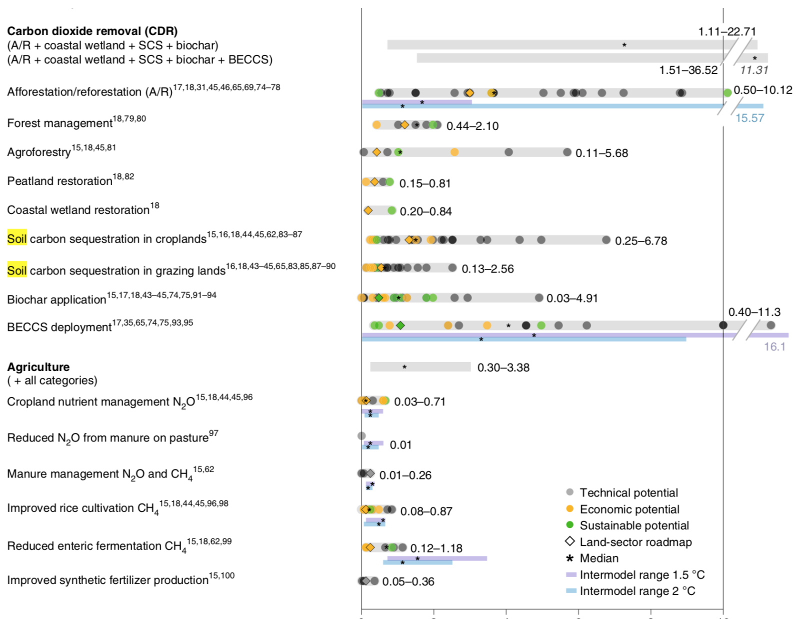
[Update March 1, 2020] Thank you to all the people who have so far contributed questions and comments to this gDocument so far. I have done my best to incorporate your feedback into the current version, and to keep the document clean I have resolved all the existing comments. Thanks specifically to those who have contributed so far:

Spencer Adler
Jacob Borrajo
Sarah Sclarsic
Eric Scott
Ryan Shea

Research ToDos

This initial draft raised more questions than answers. Specifically, open questions are:

- Correct some of the early numbers to make sure we're being consistent with talking about tons of CO2, not tons of carbon.
- Reading up on the synthbio methane reduction work by Mary Lidstrsom, who gave an excellent talk at the BU Climate symposium. The talk link [is here] (starts 4:56:00) - According to the synbiobeta link below, she is working with LanzaTech on this
- What does it really mean to sequester 2-3gigatons by changing the carbon retention by 0.4%, as per the 4 per 1000 project? ([link])
    - This sounds very interesting but there are many aspects of the biology I don't understand
- Jeremy Freeman shared this cool paper, "Contribution of the Land Sector to a 1.5C World" [(Roe et al. 2019)], which likely has a perspective on soil carbon sequestration. Need to read
    - Fig4 is a doozy



- Recent Carbon Nanotube work out of MIT ([MIT Daily link])
- Sarah Sclarsic just shared this very interesting update for Soil Tech: https://synbiobeta.com/partnership-between-locus-ag-and-nori-sets-the-stage-for-monetizing-carbon-farming/
    - [Locus' flagship product], claims significant root growth, similar to Ideal Plants out of the Salk
    - Locus is a B corp, interesting
- Conductive materials such as copper are also super valuable. Need to study that further.

- Biomaterials review paper: https://www.sciencemag.org/news/2020/02/living-cement-medicine-delivering-biofilms-biologists-remake-material-world
- Need to add section on pure carbon materials
- What are the big oil companies doing for “low carbon futures?” PR stunts or not, it is still interesting.
    - One example from Sarah Sclarsic: https://www.cemvitafactory.com/

Collections of lists/whitepapers

The Carbon180 Paper

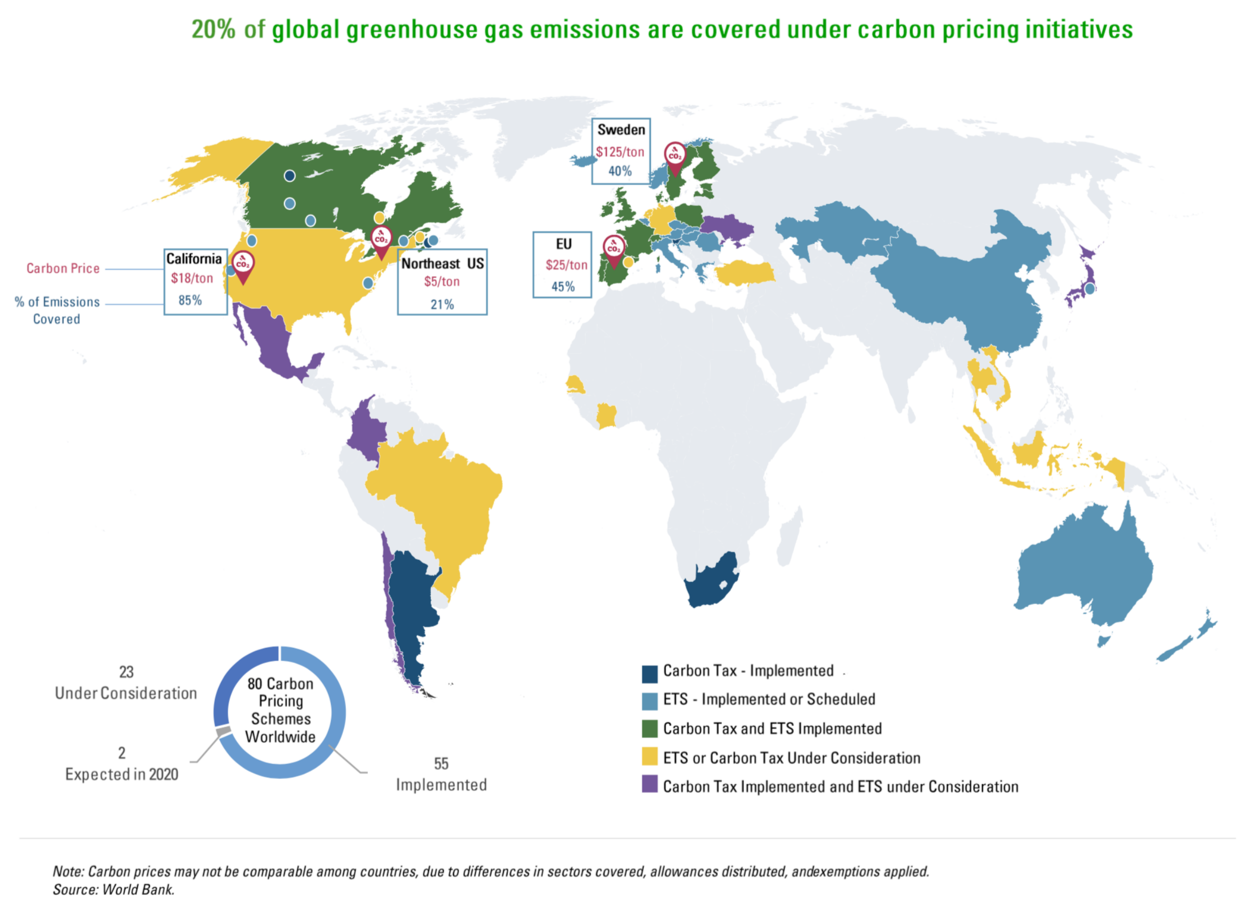
Toly: When was this published?

The HyperGiant "Algae Is the New Green"

It sells the idea of a micro algae reactor, 1.5tons per year

SynbioBeta : https://synbiobeta.com/exploring-solutions-to-climate-change-with-synthetic-biology/

CB Insights “What is GeoEngineering” ([link]()), the relevsant companies have been added to the spreadsheet



Source: Goldman Sachs “Investing in Climate Change” Global Macro Research Issue 85 Jan 30 2020

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