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Original Paper

A Review of Efforts towards Achieving Carbon Negativity

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Abstract

The purpose of this study is to better understand different approaches to achieving carbon negativity, in which more carbon dioxide is removed from the atmosphere and oceans by a process in comparison to what is released. This was examined by analyzing 287 submissions to the XPRIZE Carbon Removal competition, a four year contest focused on approaches to removing carbon dioxide from the atmosphere and oceans on a gigaton scale. The 287 teams analyzed were Qualified Competitors, meaning they demonstrated a working carbon removal solution, estimated costs at full scale, and made a case and plan for scaling and deploying their solutions at megaton or gigaton per year capacity. Results showed that 129 teams used agriculture and forestry in their approaches, while 59 used new technology, 52 used chemical approaches, 49 used Direct Air Capture (DAC) technology, 45 used the cultivation of ocean plants, 39 used geology, 38 used biochar, 29 used burial and underground storage, and 14 used bamboo and hemp. The majority of teams fit into two or more categories, and only five teams did not provide enough information to be categorized. In conclusion, approaches to carbon dioxide removal incorporating agriculture and forestry are most widely used, but approaches from all categories need to be used in conjunction in order to eventually achieve carbon negativity.

Keywords

XPRIZE carbon removal, carbon negativity, negative emissions technology (NET), direct air capture (DAC) technology, greenhouse gas reduction

1. Introduction

Increased amounts of atmospheric concentrations of greenhouse gases produce a warming effect for the planet. From 1990 to 2019, the total warming effect of greenhouse gases added by humans to the Earth's atmosphere increased by 45%, and the warming effect from carbon dioxide alone increased by 36%. As a result, achieving carbon negativity is crucial to slow the effects of climate change. For a process to be considered carbon negative, more carbon dioxide is removed from the atmosphere than what is emitted through carbon capture, sequestration, or avoidance (U.S. EPA, 2022).

XPRIZE Carbon Removal is a four year global competition that allows teams from anywhere in the world to submit ideas for removing carbon dioxide from the atmosphere and oceans and sequestering it sustainably, or preventing carbon dioxide emissions from initially being released. The competition requires teams to demonstrate their idea at a scale in which at least 1,000 tons of carbon dioxide are sequestered each year, model their costs at a scale of 1,000,000 tons of carbon dioxide per year, and show a pathway to achieving a scale of 1 gigaton of carbon dioxide removed each year in the future. Registration opened on April 22nd, 2021, and will close on April 22nd, 2025 (XPRIZE, 2022).

Since XPRIZE Carbon Removal's launch in 2021, 1,133 teams have entered the competition from around the world (Figure 1). 398 teams submitted air solutions, 367 submitted land solutions, 217 submitted ocean solutions, 121 submitted rock solutions, and 29 submitted solutions regarding monitoring, reporting, and verification. Of these 1,133 total teams, 287 were considered to be Qualified Competitors, meaning they had demonstrated a working carbon removal solution, estimated costs at full scale, and made a case and a plan for scaling and deploying their solutions at megaton or gigaton per year capacity (Figure 2). Of these 287 Qualified Competitor teams, 78 submitted air solutions, 119 submitted land solutions, 55 submitted ocean solutions, 33 submitted rock solutions, and two submitted solutions regarding monitoring, reporting, and verification (XPRIZE, 2022).

Figure 1. Location of the 1,113 Teams Entered in the XPRIZE Carbon Removal Competition

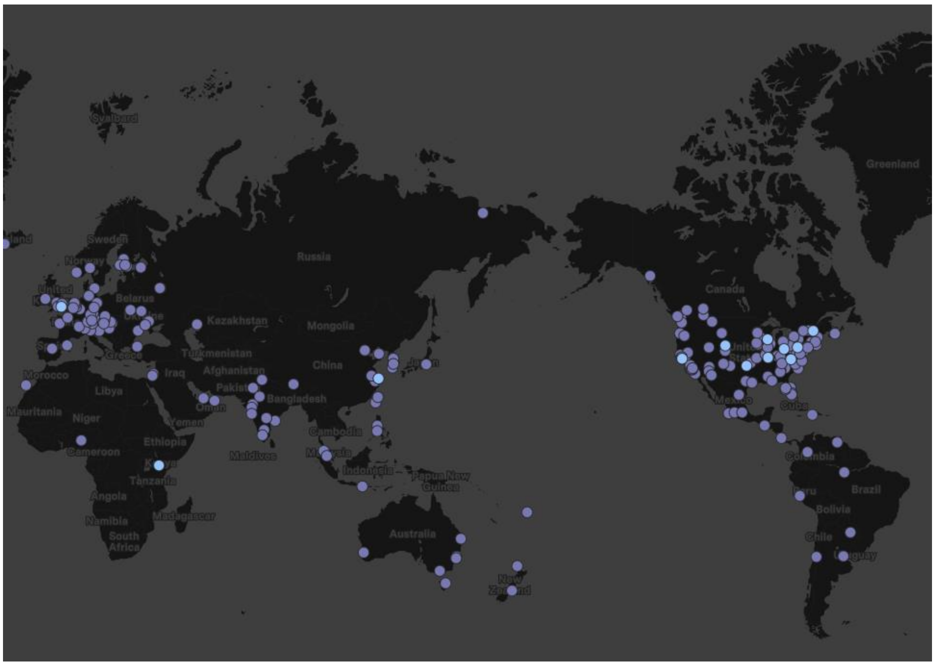

Figure 2. Location of the 287 Qualified Competitor Teams Entered in the XPRIZE Carbon Removal Competition

2. Methods

To better understand different approaches to carbon negativity, the 287 Qualified Competitor entries submitted to the XPRIZE Carbon Removal competition were analyzed. Each submission was reviewed on the official XPRIZE website and information was recorded about each team's name, location, members, associated companies and institutions, and the approach summary for their entry. If details about a submission were not available on the XPRIZE website, team members or their associated companies were searched on LinkedIn in order to better understand their background and hypothesize their approach. If no further information was available online, team members were emailed and asked to respond with a general summary of their entry. Then, teams were categorized by their approaches into nine different categories: agriculture and forestry, chemical approaches, the cultivation of ocean plants, direct air capture, geology, biochar, burial and underground storage, and bamboo and hemp.

3. Results

Many of the 287 teams fell into two or more of the nine categories listed above. Only five teams had little to no information available about their approach, and were therefore unable to be categorized (Table 1).

Table 1. Approach Categories for the 287 Qualified Competitor Teams Entered into the XPRIZE Carbon Removal Competition

Approach Summary	Number of Teams	Percentage of Teams

Agriculture and Forestry	129	44.9%
Geology	68	23.7%
New Technology	59	20.6%
Chemical Approaches	52	18.1%
Direct Air Capture (DAC) Technology	46	16%
Cultivation of Ocean Plants	45	15.7%
Biochar	38	13.2%
Burial and Underground Storage	29	10.1%
Bamboo and Hemp	14	4.9%
No Information	5	1.7%

3.1 Agriculture and Forestry

129 teams submitted an approach to achieving carbon negativity that incorporated agriculture and forestry. Trees, crops, and plants in general are some of the most important carbon sinks in the world, so it makes sense that agriculture and forestry-based approaches are the most prominent carbon-negative solutions. Some teams are focusing on afforestation and restoring natural ecosystems to peak productivity. For example, team Bison Underground from Norman, Oklahoma associated with the University of Oklahoma with members Lily Pfeifer, Steven Adams, Alex Sodeman, Andrew Oordt, Cansu Floyd, and James Epperson seeks to take unusable organic material from farms and cover crops and turn them into an injectable, nutrient-rich material that is then deposited deep into farming soils. This process sequesters carbon into the soil long-term and limits the addition of new carbon added to the atmosphere by prohibiting surface decomposition from occurring. This solution provides rapid soil and crop health restoration, improves resiliency of farms against extreme weather events, enhances crop yields, decreases need for synthetic fertilizers and irrigation, and increases agricultural biodiversity and food security (XPRIZE, 2022).

In addition, 38 of the total 129 agricultural and forestry approaches look to use agriculture to quickly grow organic matter, which can then be pyrolyzed into a stable form of nutrient-rich carbon: biochar. Biochar can be buried underground to sequester carbon for hundreds of years while simultaneously rejuvenating the soil quality. Biochar is a carbon-rich product, resulting from the pyrolysis of biomass. In essence, one can take almost any organic matter, such as crop trimmings or livestock wastes, and thermo chemically decompose it through high temperatures in the absence of oxygen. The resulting biochar product is highly nutritious and makes for great soil amendments, providing energy, supporting water retention, and increasing crop yields. At the same time, the pyrolysis process has the ability to stabilize the carbon within biomass before the decomposition process begins—some estimates hold that biochar, having a half-life of 1000 years, is able to sequester carbon within the soil for millenia (Spokas, 2010). Woolf et al. (2010) calculated that biochar has the potential to make a significant contribution to mitigating climate change. According to them, with current amounts of feedstock availability, biochar has the potential to avoid 1.8 gigatonnes of CO_2-equivalent emissions every year.

Team Takachar from Kirinyaga, Kenya associated with the University of British Columbia, Safi Organics Private Unlimited, Cornell University, Massachusetts Institute of Technology, and Jomo Kenyatta University of Agriculture and Technology utilized biochar in their submission. Team members Kevin Kung, Amit Sharma, Hannah Dye, Joyce Kamande, Samuel Rigu, and Vidyut Mohan have built low cost and portable hardware and control systems that enable the village-based production of customizable biochar-based fertilizers using locally available crop residues and labor. This fertilizer blend helps rural smallholder farmers improve their yield by up to 30% and net income by 50%, as well as enables them to access carbon removal credits which benefits traditionally underserved communities (XPRIZE, 2022).

Furthermore, 14 of the agricultural and forestry approaches incorporated the cultivation and utilization of some of the fastest growing plants in the world: bamboo and hemp. According to a technical report by Lugt et al. (2015), bamboo holds a multitude of carbon-storing characteristics: the reforestation rate of bamboo is much higher than softwood; its root system is markedly extensive, allowing bamboo to store more CO_2 in the underlying soil; and because bamboo is a grass, the harvesting of bamboo stems aboveground doesn't kill the plant and release below-ground carbon. As for hemp, Catherine Wilson, board member of the European Industrial Hemp Association, affirms the plant's environmental benefits: hemp is one of the top crops for biodiversity friendliness as it restores soil health; most importantly, industrial hemp can absorb up to 10.5 tonnes of CO_2 per hectare (Wilson, 2019). These two plants have applications in many industries, lowering the carbon footprint of fields such as construction, bioplastics, and biofuels.

Team C-Squared from Blacksburg, Virginia, associated with Virginia Tech, the Max Planck Institute, Globaia, and the Edmund Hillary Fellowship, has incorporated bamboo growth into their submission. Team members Esteban Londono, Adriana Buitrago, Gregory Marggraf, Manno Franca, Salome Sabogal, and Ximena Londono de la Pava seek to sequester carbon from the atmosphere by crowd-farming bamboo, storing the carbon by building bamboo houses, and transforming the world's housing deficit into a "carbon warehouse" (XPRIZE, 2022).

3.2 Geology and Burial and Underground Storage

Carbon mineralization is the process in which carbon dioxide is converted into a solid mineral, such as carbonate, preventing any possible CO_2 leaks later. This process occurs naturally, but there are ways to speed it up, such as injection of CO_2 into rock formations deep underground or by exposing CO_2 to broken rocks, like mine tailings, at the surface (USGS, 2019). According to the European Commission, studies have shown that carbon dioxide can be safely sequestered underground for thousands of years—it is even estimated that there is enough capacity to theoretically store all of the CO_2 emissions from fossil fuel usage underground (O'Callaghan, 2018). However, some concerns with this method are that CO_2 could potentially leak back out into the atmosphere or natural water supplies, and that pressurizing CO_2 underground could induce seismic activity.

A similar result can be achieved by burying organic matter, instead of CO_2, either underground or underwater. Burying biomass in sediments allows this carbon to exit the biosphere-atmosphere carbon cycle, and thus prevents any greenhouse gas emissions within the natural systems (Mendonça et al., 2017). Overall, a combination of DAC technology and carbon burial can be combined to capture and sequester large amounts of carbon dioxide currently polluting the atmosphere.

68 teams took a geological approach to their XPRIZE Carbon Removal entries, with 29 of these teams also incorporating burial and underground storage. Milestone award winners Verdox and Carbfix are teaming up to bring DAC technology and carbon mineralization to the forefront of the industry. Based in Boston, Massachusetts, team members Jonte Boysen and Martin Voigt are electrochemically removing CO_2 from the atmosphere and turning it into stone underground (XPRIZE, 2022). Verdox's carbon capture and removal technology is reportedly 70% more energy efficient than conventional approaches, and in conjunction with Carbfix's 10 years of carbon storage, multiple tons of carbon can be removed from the atmosphere and permanently stored underground (Boysen, 2022).

3.3 New Technology

Whereas most carbon-removal solutions utilize a pre-existing technology, many applicants to the XPRIZE Carbon Removal competition developed novel methods to capture and sequester CO_2. These teams designed original and unique technology that couldn't be organized into any of the other, broader categories. 59 teams utilized some form of new technology in their carbon removal solutions.

For example, team Black Concrete Materials is enhancing construction materials through the infusion of CO_2. Members Xiaopan Qiu, Yulin Xi, Dongxu Chen, Jianjun Zhang, Jie Li, and Siqi Lan plan to capture CO2 and elevate its temperature and pressure until it reaches a supercritical state. From here, they plan to use concrete to absorb this supercritical CO2, giving this new material the strength and durability exceeding that of carbon steel (XPRIZE, 2022). Another example of new technology can be seen in the team Super Chimney. This team, based in Wayne, New Jersey and headed by Michael Pesochinsky, suggests that constructing 25,000 5 kilometer-tall chimneys across the planet can facilitate enough heat exchange across the atmosphere to remedy global warming (XPRIZE, 2022). Overall, some of the most out-of-the box ideas come out of this "New Technology" category. But, unprecedented ideas are usually what spur the greatest changes. Like the saying goes, "The day before something is a breakthrough, it's a crazy idea."

3.4 Chemical Approaches

The ocean, as vast and populated as it is, is an undeniable carbon sink across the world. In fact, the National Oceanic and Atmospheric Administration estimates that 50-80% of the oxygen on Earth comes from the ocean, specifically from photosynthetic plankton (NOAA, 2021). This means that incredible amounts of CO_2 are being captured by phytoplankton, converted into other forms of carbon, and eventually sequestered in the deep ocean.

52 teams used chemical approaches utilizing CO_2 in their XPRIZE Carbon Removal submission. For example, team AC Carbon Capture from Oslo, Norway associated with Bilfinger and Denmark Technical University has designed the "AC Carbon Capture Process", a new cost efficient CO_2 air capture technology. Tord Hansen states that the concept comprises CO_2 capture through ammonium bicarbonate formation and precipitation, combined with CO_2 regeneration by thermal decomposition of the ammonium bicarbonate solids at an elevated pressure and temperature. When deployed to full scale, it is hypothesized that this process will have a total CO_2 capture rate of 130 tons of CO_2 per hour, equivalent to about one million tons of CO_2 per year due to its 85-90% efficiency rate (XPRIZE, 2022).

In the ocean, carbon dioxide isn't only being drawn down by primary producers, however; these greenhouse gasses are able to dissolve into the seawater itself. As atmospheric CO_2 levels rise, these molecules can dissolve in seawater, converting into carbonic acid. Some teams, such as the San Carlos, California-based EBB Carbon, see this reaction as an opportunity to sequester carbon. Members Matthew Eisaman, Ben Tarbell, Brent Hall, Kyla Westphal, Sophia Hedeman, and Todd Pelman plan to chemically pump this acid out of the ocean and sequester it, lowering CO_2 concentrations in the ocean and in effect the atmosphere too (XPRIZE, 2022).

3.5 Direct Air Capture (DAC) Technologies

Direct air capture (DAC) technologies have a promising future, being able to draw CO_2 directly out of the atmosphere. There are two main approaches to DAC of carbon dioxide: one using a liquid sorbent and the other using a solid filter. Liquid systems stream air through chemical solutions, which are able to remove and dissolve the CO_2, while returning the rest of the air back to the atmosphere. Solid systems utilize solid sorbent filters that chemically bind with atmospheric carbon dioxide, while also allowing the rest of the air to pass through (IEA, 2021).

46 teams revolved their approach around DAC technology. For example, Team Carbyon from Eindhoven, Netherlands with members Arno Van Hoof, Dries Van Eyck, Gerben Van Straaten, Hans De Neve, Jeroen Van Dijck, Vinayaraj Ozhukil Kollath, Marco Arts, Aswin Schouten, Dick Van Deijck, Jasper Simons, Luuk Van Voorst, Ugur Goktolga, and Wim Verstappen has developed the next generation of equipment to capture CO2 directly out of ambient air, enabling extreme energy efficiency and low manufacturing costs. This is an economically viable carbon removal solution that can be scaled up worldwide, in any location, with a small ecological footprint (XPRIZE, 2022).

3.6 Cultivation of Ocean Plants

The cultivation of ocean plants, such as algae, kelp, and seaweed, is another carbon negativity effort: the algae absorbs CO_2 within the ocean that originally came from the atmosphere and eventually sinks to the ocean floor via the biological pump, storing carbon in the deep ocean for centuries. According to Haoyang (2018), because algae is such a fast-growing group of photosynthesizers, the cost and effort of cultivating them is very little. On top of that, ocean-based algae contributed to 45% to 50% of the total CO_2 absorbed by the earth's biosphere.

45 teams utilized the cultivation of ocean plants in their submission. For example, team Marine Permaculture SeaForestation from Woods Hole, Massachusetts, associated with the Climate Foundation, with members Brian Von Herzen, Micha Van Winkelhof, Samuel Zak, and Theresa Theuretzbacher, has utilized the cultivation of algae in their submission. In this approach, deepwater nutrients are accessed to enhance the growth of macroalgae, fixing carbon in ocean waters. This enables the cultivation of seaweed at large scales offshore in mostly empty oceans, ordinarily deprived of nutrients and where there is little primary productivity. Seaweeds are harvested to create biostimulants, and the biomass that falls off the seaweed lines naturally sink to the seafloor and sequester carbon for hundreds to thousands of years (XPRIZE, 2022).

4. Discussion

The carbon credit market essentially makes carbon a commodity and allows for units of offset to be sold and bought by others to reduce their carbon footprint. One regulation of greenhouse gas emissions involves a cap-and-trade program, which sets a limit on the amount of greenhouse gases that may be emitted and creates a market for the offset carbon. When one company is able to remove a unit of carbon, another company would be able to buy this unit of offset carbon to mitigate their own emissions. A cap-and-trade program is an example of a mandatory/compliance market where mandated caps are established and regulated by an authority. There are also voluntary offset markets where carbon offsets are purchased voluntarily by those who take responsibility for their own emissions. Voluntary offset markets have become more recognized as the benefits are seen by individuals outside of regulated companies in mandatory markets (Greenhouse Gas Management Institute, 2020). California currently has an existing cap-and-trade program that has a preset declining annual limit on greenhouse gas emission sources. The declining limit set a goal to reduce emissions by 15% and generate an economical motivation to emit less greenhouse gases into the atmosphere (California Air Resources Board, 2022).

No particular solution here is perfect—every method has its own benefits and drawbacks. For example, DAC looks to draw CO_2 directly out of the atmosphere, but CO_2 only constitutes a small 0.04% of the atmosphere's total volume (Buis, 2020). As such, DAC has a much higher energy cost relative to other carbon capture technologies. Looking towards agriculture and forestry solutions, many of these methods focus on storing carbon-rich biochar in agricultural soils, sequestering carbon while improving soil health. However, there is still some uncertainty in biochar's actual carbon storing efficiency. For example, in a 10 year study of boreal forests, it was found that adding biochar led to soil degradation as well as an increase in soil microbe activity, leading to net CO_2 release (Wardle et al., 2008). On top of that, afforestation holds its own carbon storing uncertainties. Even the Amazon rainforest, thought to be the "lungs of the Earth", is now emitting more CO_2 than it absorbs, due to deforestation, warming, and moisture stress (Gatti et al., 2021). Likewise, ocean chemistry-based carbon removal solutions are surrounded by unknowns. Science just doesn't yet know how the ocean will react to drastic changes in its carbon chemistry, as removing some chemicals while enhancing others could have drastic effects on the food web, nutrient composition, sedimentation rates, and much more.

This study of carbon negative efforts made by the 287 Qualified Competitor teams in the XPRIZE Carbon Removal competition found that most teams fell into two or more different approach categories. Along with the number of different approaches, it is imperative to ensure that these methods are within the guidelines of environmental policies and are considerate of environmental justice matters. The competition states that all teams must uphold reasonable standards and follow all applicable laws while they participate in the competition. For example, in December of 1970, the United States established the Environmental Protection Agency (EPA) to create a foundation of laws for protecting the environment and public health. Under the EPA, there are laws like the National Environmental Policy Act (NEPA) that encompass a broad framework for environmental protection. This law would require that an environmental review process takes place before a decision is made to build anything to identify any possible significant health/environmental risks (U.S. EPA, 2022).

5. Conclusion

In conclusion, the overwhelming majority of approaches to the XPRIZE Carbon Removal competition incorporated agriculture and forestry into their submission. Agriculture and forestry is a very viable means of achieving carbon negativity, because plants, under normal conditions, are excellent carbon sinks. As discussed above, biochar can be buried underground to improve soil quality while also sequestering carbon for hundreds of years. Additionally, industrial hemp can absorb up to 10.5 tonnes of CO_2 per hectare and bamboo has a fast reforestation rate, extensive root system, and carbon-safe harvesting properties.

However, agriculture and forestry, even when incorporating the use of biochar and fast growing materials such as bamboo and hemp, cannot be relied on alone. Achieving carbon negativity is vastly difficult, because it is impossible to release negative amounts of carbon dioxide; net emissions must be created, and this must be done at the gigaton scale. To truly have a chance of drawing down carbon dioxide from the Earth's atmosphere and oceans, all approaches, including geology and burial and underground storage, new technology, chemical approaches, direct air capture technology, and the cultivation of ocean plants as discussed in this paper as well as other approaches that have not yet been analyzed, must be used in conjunction with one another for change to legitimately be achievable. The challenge increases due to environmental uncertainties and the various benefits and drawbacks of each, but the ultimate end goal of achieving carbon negativity should still be strived for. This analysis provides hope that there are carbon negativity solutions that are truly viable.

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