Carbon Dioxide Removal

Reducing our Footprint

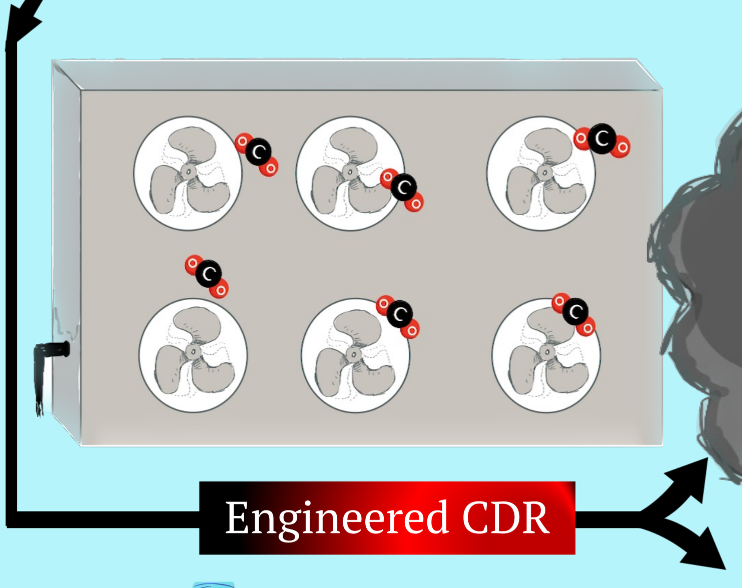
Carbon dioxide removal (CDR) plays a critical role in tackling the world's climate crisis and achieving net-zero carbon emissions by 2050. [1]

CDR refers to approaches to capture carbon dioxide (CO_2) directly from the atmosphere and store it in reservoirs, transform it into value-added products, or convert it into fuels with the goal of creating negative emissions. The developments of CDR methods will help the United States become a net-zero carbon economy by mid-century. [2]

CURRENT CDR APPROACHES

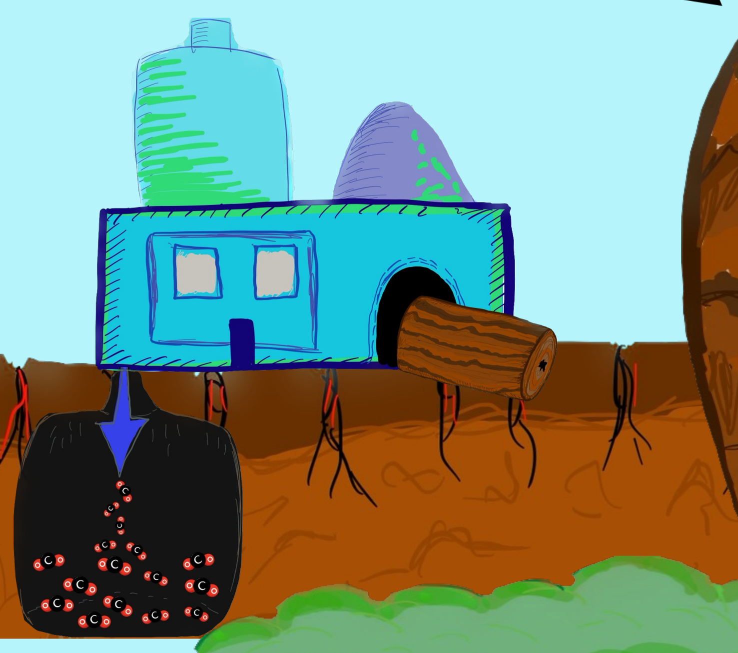
Carbon dioxide removal can address two problems that reduction of CO_2 emissions cannot address alone: today's elevated levels of CO_2 in the atmosphere exceed the ability of nature to remove it from the environment; CDR approaches support the restoration of disrupted ecosystems due to human activity. [3]

CURRENT CARBON DIOXIDE REMOVAL METHODS



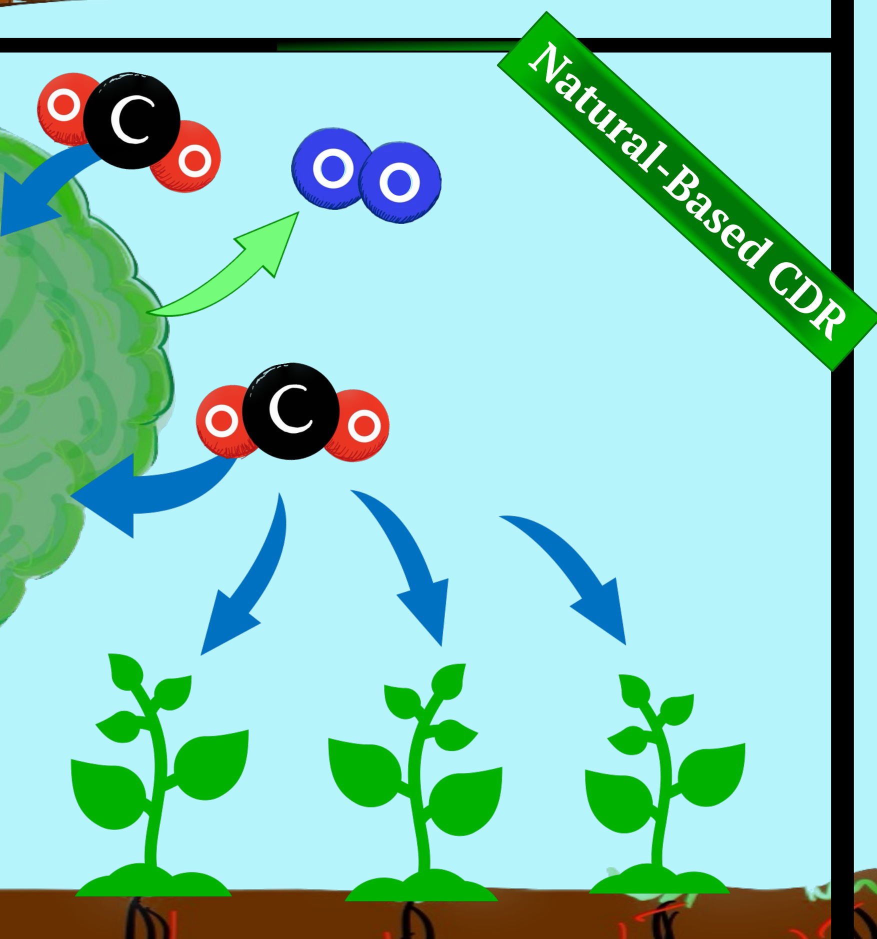
DIRECT AIR CAPTURE WITH STORAGE

- Chemically scrubbing CO_2 directly from the atmosphere and storing it underground or in long-lived products. [2,3]
- Large fans move ambient air through filters that use chemical absorbents to produce pure CO_2 streams that can be later stored. [3]
- Direct air capture has the potential to address emissions from distributed sources (e.g., gasoline) as well as point sources (e.g., power plants).



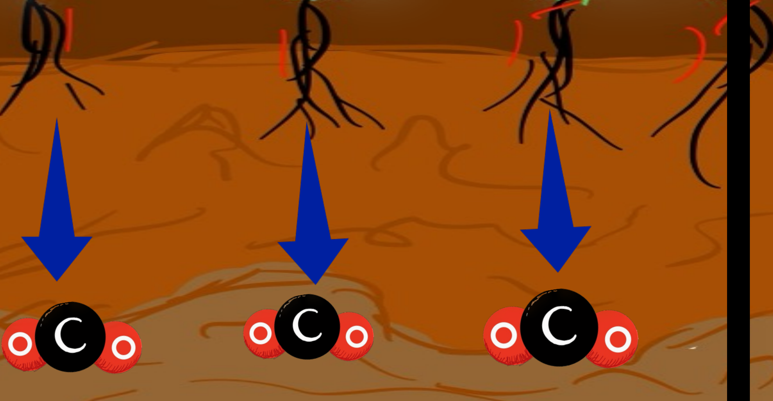
BIOMASS CARBON REMOVAL AND STORAGE

- Uses biomass (e.g., plants, algae) to generate electricity and fuels, while CO_2 emissions are captured and stored in a manner that prevents entry to the atmosphere, for example, underground or in long-lived products like low-carbon concrete. [2,3,4]
- Farming, forestry, and waste management generate large quantities of biomass that can be used as a source of bio-energy while also storing carbon emissions. [4]
- There are vast locations for carbon storage in all regions of the world.



AFFORESTATION AND REFORESTATION

- Exploiting photosynthesis, the ability of plants to convert CO_2 into oxygen (O_2), by newly growing or regrowing forests to remove CO_2 from the air and store in the form of biomass. [2]
- Restoration, expansion, and management of forests increase carbon uptake, boosting photosynthesis, extracting CO_2 from the atmosphere and storing it in soils and in wood. [3,5]
- Afforestation and reforestation restore habitat for numerous species.



SOIL CARBON SEQUESTRATION

- Farming practices and crop growth that increase carbon storage in soils.
- Technology for carbon capture and storage already exists in the natural functions of plants (photosynthesis and plant growth). [6]
- Relies on plant photosynthesis as a first step towards the CO_2 removal from the atmosphere. [6]
- The storage of carbon in soil biotic pools is longer-lived and there exists enormous carbon storage capacity. [6]
- Promotes soil health and soil fertility, making farming more effective. [6]

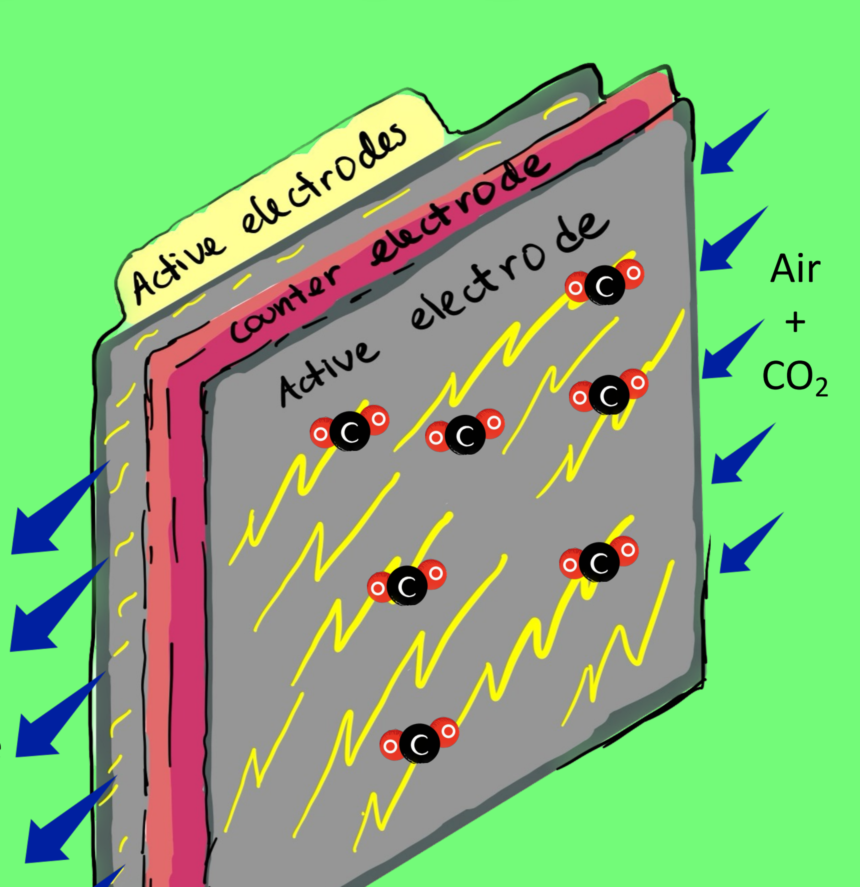
OCEAN-BASED CDR

- Acceleration of natural carbon cycles in the oceans through a combination of biotic and abiotic approaches, which extract CO_2 from the atmosphere and store it into the ocean depths and marine sediments or in land. [2,8]
- Marine and coastal ecosystems sequester carbon faster and far more efficiently than terrestrial forests. [7]
- The addition of minerals can lead to alkalinity enhancement which accelerates the ocean's ability to dissolve atmospheric CO_2 and, in some cases, reduces ocean acidity. [8]
- Increment of biological agents like seaweed and phytoplankton increases carbon storage and oceanic deacidification. [8]
- Oceans have diverse biogeochemical cycles, and ocean circulation has longer timescales than the atmosphere, which means that additional anthropogenic carbon could be potentially stored in the deep ocean or on the sea floor. [7]

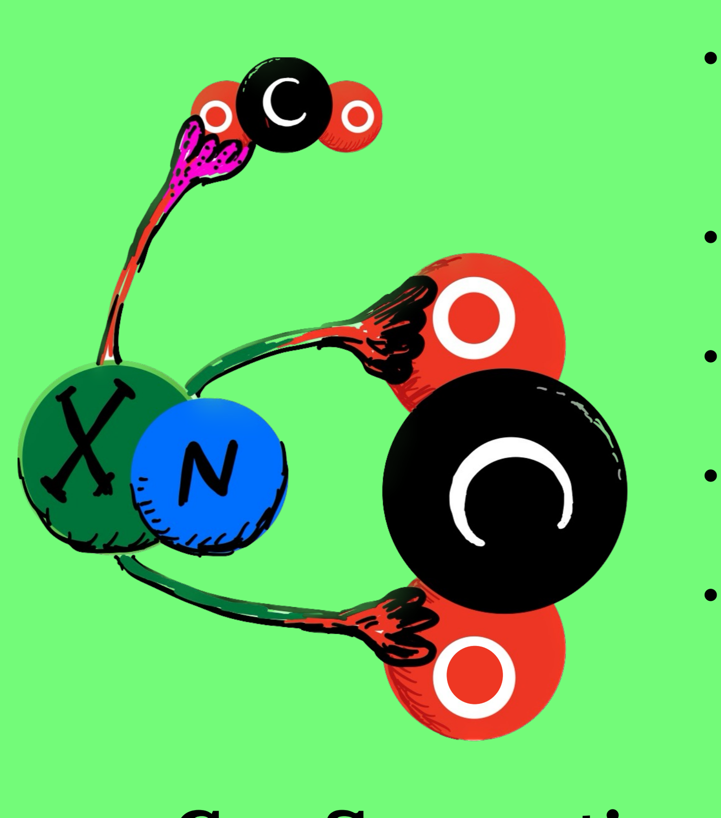
NEW CDR DEVELOPMENTS

Electrochemical Cells for High Efficiency Carbon Capture

- Air is passed though a stack of charged electrochemical cells (i.e., a large, specialized battery), the electrodes absorb CO_2 from the passing air as the cells charge and a pure sample of CO_2 gas is released as the cells discharge. [9]
- Potential to react with carbon at very low concentrations (from 0.6% up to 10%) while other methods target carbon at high concentrations (>10%). [9]
- No need for special operating environments. The electrochemical cells operate at room temperature and with ambient air pressure to return a stream of pure CO_2. [9]



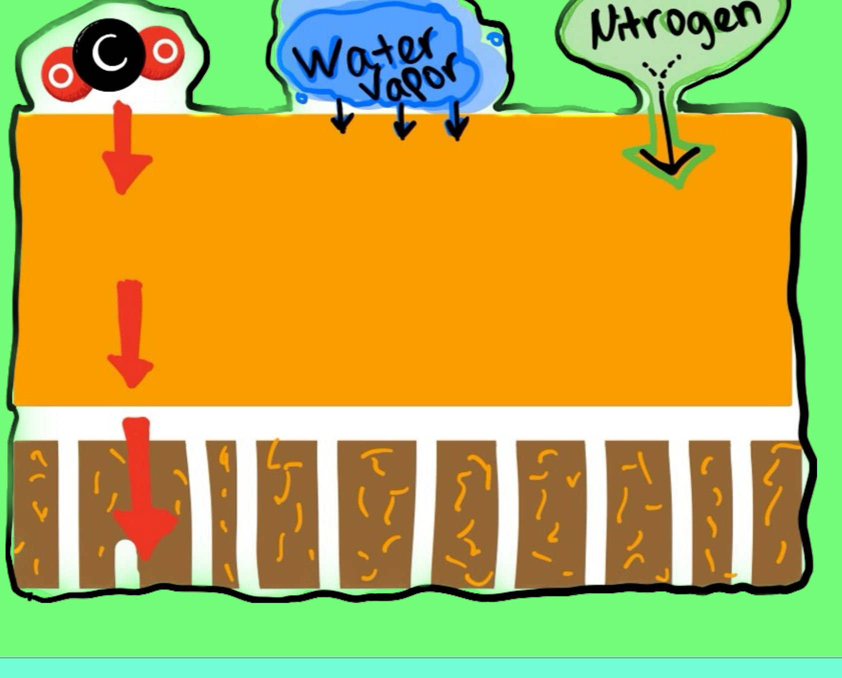
Chemical Binders



- Looks for molecules that can bind CO_2 and form strong chemical bonds from everyday air; these molecules are known as "binders." [10]
- Main goal is to find molecules that can "grab" CO_2 from everyday air. [10]
- Electrochemical methods are efficient at capturing CO_2 at low concentrations.
- The resulting CO_2 compounds can be converted into materials (e.g., carbonates) and fuels. [10]
- Generating energy from the CO_2 bound molecules can be expensive, but as this method gains popularity, it will become more economical. [10]

Polymer Gas-Separation Membranes

- Use solubility properties of membranes to achieve different levels of CO_2 selectivity and permeability and to remove CO_2 from mixed gases. [11]
- Polymer membranes have a strong chemical affinity for CO_2. [11]
- The ultra-selective and ultra-permeable membrane works by filtering CO_2 faster than other mixed gases. [11]
- The membranes are low cost and easy to manufacture.



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Carbon Dioxide Removal: Removing our Footprint

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Greenhouse gases are directly related with global warming and climate change. The ongoing addition of these gases to the atmosphere increases global temperatures and negatively impact ecosystems. Carbon dioxide gas comprises the biggest fraction and the longest lifetime of greenhouse gases in the atmosphere, thus, reducing CO_2 emissions and removing CO_2 from the atmosphere is a critical step towards addressing the world's climate crisis. Numerous engineered and natural-based approaches have been developed and proposed over the last decades, among them, direct air capture, biomass carbon removal and storage, afforestation and reforestation, soil carbon sequestration, and oceanic carbon sequestration. Additionally, new research is being performed to develop more efficient ways of removing and storing carbon dioxide, particularly, from air with low carbon dioxide concentrations. New research ranges from electrochemical cells, carbon capturing molecules, and polymer membranes. The information in this paper supports the infographic titled "Carbon Dioxide Removal: Removing our Footprint," which presents five current leading approaches of removing and storing carbon dioxide from the atmosphere and three recent scientific and technological research projects in carbon dioxide removal.

I. INTRODUCTION

Reducing the emission of carbon dioxide (CO_2) into the atmosphere and permanently removing CO_2 from the atmosphere are imminent steps toward solving the world's climate crisis and achieving net-zero emissions by mid-century. [1] Anthropogenic (originating from human activity) CO_2 is directly related to the burning of fossil fuels, which have significantly increased over the last century. The means through which humans have been generating energy since the industrial revolution, have increased the concentrations of greenhouse gases in the atmosphere such as carbon dioxide — among other things. To further explain, greenhouse gases are gases that can trap heat in the atmosphere. CO_2 is not the only greenhouse gas, methane, nitrous oxide, and chlorofluorocarbons, among others, also belong to this group of gases. However, CO_2 occupies the highest atmospheric concentration, and it also possesses the longest atmospheric lifetime, making it the biggest contributor to global warming and extreme weather.

Earth has natural cycles to remove and sequester CO_2 from the atmosphere. Nevertheless, human activity often interferes with these natural carbon cycles, for example, ongoing deforestation diminishes the carbon dioxide uptake of plants via photosynthesis. Human activity has grown so significantly in the last fifty years that the elevated levels of CO_2 in the atmosphere exceeds the ability of nature to remove CO_2 and store it. Besides, increasing temperatures also impacts natural cycles, such as the rate of plant growth and atmospheric circulation, which in part can contribute to scenarios of extreme weather – the latter is already present in the current world's climate.

Reducing the emissions of CO_2 into the atmosphere is not enough for nature to remove CO_2 by itself and for global climate to stabilize. Thus, implementing and developing methods to remove and store CO_2 from the atmosphere is crucial to address the climate crisis and achieve net-zero carbon emissions by 2050.[2] Thankfully, approaches have been developed and are in place to fulfill this goal. These approaches are carbon dioxide removal (CDR) methods. In this paper, five current leading CDR methods are presented. Three recent scientific and technological research projects and developments in CDR are also presented.

II. CURRENT CDR APPROACHES

Carbon dioxide removal (CDR) refers to approaches to capture CO_2 directly from the atmosphere and store it in geological, biobased and ocean reservoirs or in value-added products to create negative emissions.[2] Such approaches will help the United States tackle the global climate crisis and become a net-zero carbon economy by mid-century. It is important to note that CDR approaches should be implemented sustainably, in other words, the removal technologies should also account for their own emissions while in operation. To support the information presented in the infographic by the same name of this paper, five main current methods are explored, where two of them, Direct Air Capture with Storage (DACS) and Biomass Carbon Removal and Storage (BiRCS), are engineered based methods, and the rest, Afforestation and Reforestation, Soil Carbon

Sequestration, and Ocean-Based CDR, are natural-based methods.

A. Direct Air Capture and Storage

Direct air capture and storage (DACS) refers to ways of chemically scrubbing carbon dioxide from the atmosphere and storing it underground or in products.[2, 3] Direct air capture has the potential of addressing carbon emissions from distributed sources like gasoline and from point sources like power plants. A major benefit of using DACS is that the capture of CO_2 does not require specific locations, which can reduce the need of pipelines (further damage to the ecosystem) from the site of capture to the sequestration reservoir. Mainly two types of DACS can be implemented to remove CO_2 from the air, whose application are only dictated by the properties of the air samples to use. For air with high concentrations of CO_2, physical chemical solvents are predominantly used, while for air with low concentration of CO_2 require chemical bases that can react with CO_2. For example, in the simplest cases hydroxides and amines can be used.[3]

For liquid solvent systems, the two main components are the air contractors (e.g., large fans, similar to the ones used in cooling systems) and a facility that processes the extracted air to separate and storage the CO_2. Generally, the liquid solvent used in this process is a solution of potassium hydroxide which reacts with CO_2 to produce a solution of potassium carbonate. The resulting solution is then reacted with calcium hydroxide to produce calcium carbonate, which is then filtered and heated to obtain solid calcium oxide and a pure sample of CO_2 gas. The pure CO_2 is compressed and transported for storage.[3]

For solid solvent systems, the air contractor is also present which contains a solid adsorbent. The CO_2 is absorbed onto the solid sorbent. Similarly, the solid absorbent is heated where it releases the CO_2. One advantage of this process is that the solid adsorbent can be cooled and reheated to re-initiate the CO_2 capturing procedure. Systems using solid solvents are generally more expensive and they require more energy, thus, raising issues of energy disproportion (i.e., the consumption of energy by the process outweighs the benefit of capturing and storing CO_2).

The limitations associated with DACS are only financial and related to storage capacity. One future implementation proposed by the National Academy of National Academies of Sciences, Engineering, and Medicine, is that DACS facilities also process BiRCS, in such way that carbon is sequestered in the same storage system. DACS facilities are already in operation. The U.S. Department of Energy's (DOE) Office of Fossil Energy, National Energy Technology Laboratory (NETL) and Southern Company Services, operates and maintains current test facilities such as the National Carbon Capture Center in Wilsonville, Alabama.

B. Biomass Carbon Removal and Storage

Biomass carbon removal and storage (BiRCS) involves processes that use plants and algae to remove CO_2 from the atmosphere and store it underground or in long-lived products.[4] The combination of bioenergy production with carbon removal and storage can lead to net negative emission. The main idea behind BiRCS is to sequester the carbon stored by photosynthesizing biomass while producing energy.[3] BiRCS processes could capture and store 2.5-5.0 gigatons of CO_2 annually by mid-century, helping the U.S. reach its goal of net-zero carbon emissions by 2050.[2, 4]

BiRCS combines natural-based processes with engineering-based ones. Plants and algae store carbon via photosynthesis as they grow and power production plants uses them to generate energy, the resulting CO_2 emissions are sequestered via carbon capture and store in geological reservoirs.[3] Biomass can come from different sources, forests, agriculture, algae production, and organic waste. As biomass grows, it sequesters CO_2 from the atmosphere and creates negative emissions. Once biomass is produced and collected, it must be transported to a processing facility, where the conversion to heat, electricity and fuels is achieved. Moreover, biomass can be transformed into energy and fuels mainly through thermochemical and biological processes, respectively. Thermochemical processes include combustion, pyrolysis, gasification, and hydrothermal liquefaction which coverts biomass to energy. On the other hand, biological processes, fermentation, anaerobic digestion, and algae photosynthesis, convert biomass to fuels such as alcohol, methane, and hydrogen.

Once the energy and fuels are produced, the CO_2 resultant from the conversion can be stored and captured using direct air capture systems discussed in Subsection A and soil sequestration. For the production of energy, that gaseous CO_2 is released, the high concentrated CO_2 emissions can be captured using DACS and liquid solvents. In the production of fuel, 25 – 45 % of the total biomass converted into fuel is solid carbon which is produced as a byproduct. Due to the ability of solid carbon to absorb and slowly release nutrients, it can be stored in soils, increasing soil fertility, and decreasing the use of fertilizers. [3]

A few commercial-scale facilities sequestering biogenic carbon are already in operation.

Researchers at the Lawrence Livermore National Laboratory estimated that about 2.5 megatons of carbon are currently sequestered each year, which is 1000-2000 times smaller than the total BiRCS potential.[4]

C. Afforestation and Reforestation

Afforestation involves planting trees or facilitating the natural regeneration of trees on land that forests would not naturally growth by themselves. Forests are commonly referred to as the "lungs of the planet" because of their ability to transform large quantities of carbon dioxide into oxygen through photosynthesis. For some time, even before the industrial revolution, deforestation have been an ongoing activity. By cutting down trees, humans have limited the ability of nature to remove carbon from the atmosphere. As mentioned earlier, the addition of anthropogenic carbon to the decline of green areas over the years, have impeded the natural regeneration of forests. The latter being mainly a result of raising temperatures and the ongoing extreme weather.

Moreover, simply regrowing or growing new forests are not a solution alone. The selection of trees that are likely to remove more carbon dioxide in comparison to other species of trees must be also carried out, in this way the population of such trees will increase the net-biomass production, accelerating the carbon sequestration cycle.[3] It has been estimated that afforestation and reforestation could yield to a global net carbon removal of 3.4 tons of CO_2 per hectare yearly.[5] Afforestation and reforestation will also restore and create habitants for numerous species, helping the ecosystems in general.

D. Soil Carbon Sequestration

Soil Carbon sequestration depends on the execution of improved management practices that improve the concentration of CO_2 stored as soil organic matter.[6] The goal of implementing such practices is to increase the input of plant-based remains to soils and reducing the output of carbon supplies in the soil. Soil carbon sequestration uses photosynthesis of plants to remove the CO_2 from the atmosphere. On the contrary of foresting, that increases the amount of carbon in plant-biomass, soil carbon sequestration delivers carbon directly to the soil as soil organic matter, mostly in cropland and grazing lands. [6] The two-step process does not require the use of new land. Soil carbon sequestration can be applied to agricultural lands, which will end up benefitting the land health and fertility. Soil carbon sequestration has the potential to of capturing and storing 2 – 5 gigatons of CO_2 yearly.

In agricultural and grasslands, the rates of carbon input and carbon loss are affected by the soil and crop management. There are numerous ways to increase the input of carbon into the soil and to reduce the loss of carbon from the soil. These practices vary from conventional farming techniques to more technological and expensive practices. Among the most accepted and traditional techniques, there is improved crop rotations and cover cropping, which consists in planting high-residue crops, seasonal cover crops, and continuous cropping.[6] The addition of manure and compost to the soil can also input more carbon into the soil. Furthermore, the farming practice of tillage can decrease the rate of decomposition of organic matter and also protect the soil against erosion.[6]

The addition of biochar or solid carbon (produced in biomass energy generation facilities) can also increase the concentration of carbon in soils. This technological alternative can be more expensive and less accessible to farmers; however, biochar could be provided to the land managers if there is enough incentive from agencies (e.g., federal programs). Bioengineered alternatives can also be an option, for instance, crops could be bred to develop larger and deeper root system, that will eventually deposit more carbon into the soil.[6]

E. Ocean-Based Carbon Dioxide Removal

Ocean-based CDR refers to the processes of removing CO_2 from the atmosphere by combining plant growth, regeneration of coastal ecosystems, and the addition of minerals for fertilization and deacidification.[7] The ocean is remarkably efficient at absorbing carbon, and it is an integral part of the carbon cycle in the planet. Nevertheless, the increasing concentrations of CO_2 in the atmosphere have led to increase of oceanic temperatures, to increase of acidification, to oxygen loss, to changes in the current cycles and to changes in nutrients concentrations; all of which, deeply affect marine ecosystems. Ocean-based carbon removal approaches can be divided into two types abiotic and biotic.[8] The use of both abiotic and biotic components in ocean-based CDR techniques mainly focuses on amplifying the "ocean carbon pumps." [2, 8]

Abiotic approaches use the chemical and physical properties of the ocean to remove CO_2 from the atmosphere. This can be achieved through different approaches, for example, electrochemical removal, alkalinity enhancements, and artificial downwelling. Electrochemical removal consists in using electricity to extract carbon from the ocean and store it on land. Meanwhile, alkalinity enhancement consists in adding certain minerals to the ocean's water that increases the solubility of atmospheric CO_2 in seawater. Alkalinity enhancement could also help reduce acidity in the oceans. Artificial downwelling consist in the acceleration of the natural currents that carry carbon-rich water from the surface of the ocean to the depth of the Artic and Antarctic.[8]

Biotic approaches consist in adding photosynthesizing organisms in seawater to absorb carbon dioxide through their natural biological cycles and store it as biomass.[7,8] For example, seaweed can be cultivated and then submerged to the oceanic depths, sorting carbon in the seafloor. Also, the addition of nutrients to the ocean can promote the growth of phytoplankton, which will then store some CO_2 in the form of biomass.[8] The restoration of wetland and coastal ecosystems not only plays an important role in removing carbon dioxide from the atmosphere, but also provide oxygen, food, and income generation.[7] The restoration of coastal ecosystems like mangroves, salt marshes and seagrasses is an imminent step towards increasing carbon removal and storage. [7] Per unit area, coastal systems sequester carbon faster and more efficient than land forests and natural-based soil carbon sequestration. [7]

Most ocean-based CDR and ocean carbon removal approaches are just being developed and implemented. United States and Japan are two countries leading the implementation of such approaches.[8] Some companies working on the removal or carbon from the oceans with direct applications to carbon dioxide removal from the atmosphere are Vesta, Running Tide, and Planetary Technologies.[8]

III. NEW DEVELOPMENTS

New research on ways of removing carbon dioxide from ambient air and the atmosphere is boing done. Three new proposed CDR alternatives are presented: faradaic electro-swing reactive adsorption for CO_2 capture developed by researchers at the Massachusetts Institute of Technology (MIT), electrochemical capture of carbon dioxide through the use of "binders" molecules developed by researchers at the University of Colorado – Boulder, and ultra-permeable and ultra-selective CO_2 polymer membranes developed by researchers at the North Carolina State University.

A. Electrochemical Cells for High Efficiency Carbon Capture

Researchers at MIT developed a solid state faradaic electro-swing adaptive adsorption system comprising of an electrochemical cell that exploits the reductive addition of CO_2 to quinones for carbon capture. [9] As negative electrode in the electrochemical cell charges it captures CO_2 via carboxylation of quinones, and CO_2 is released while discharging. The system targets low CO_2 concentrations (as low as 0.6% and up to 10%), while other methods (e.g., DACS) require concentrations greater than 10 %.[9] This technique is based on passing air through the stack of charged electrochemical cells. The system is essentially a large battery that absorbs carbon dioxide from the passing air as the negative electrodes charge, releasing a sample of pure clean air. Once the CO_2 free air passes entirely through the device, the electrodes are discharged, and a stream of pure CO_2 gas is released, allowing to be collected. [9] The electrochemical cells are coated with carbon nanotubes made of a compound called polyanthraquinone. The system does not require special location or conditions, it operates at room temperature and ambient air pressure. One of the direct applications of the device, is to collect the pure sample of CO_2 gas and use it in the fabrication of carbonated drinks, which will potentially replace the use of fossil fuels in soft-drink factories. [9]

B. Electrochemical Capture of Carbon Dioxide; Binder Molecules

This method predicts how strong a bond will be between a CO_2 and a molecule that traps it, known as a binder. [10] An extensive electrochemical diagnosis is applied to molecules that might have some affinity to form chemical bonds with CO_2 this allows researchers at the University of Colorado – Boulder to identify which molecules form strong candidates to capture CO_2 from ambient air. [10] The method targets low concentrations of CO_2 because its main goal is to find molecules that can "grab" CO_2 from the ambient air. The resulting compounds from binding CO_2 and molecules have potential uses in carbonates production (cement), alcohol and methanol production. The diagnosis of chemical bonds is done by using an electrode to send and electron to a molecule. In the study, the researchers used a imidazolium molecule, where they remove a hydrogen atom and filling the gap with a CO_2 molecule.[10] Although, as of now, the production of such compounds can pose financial barriers, however, as the method gains popularity, it will become more accessible.

C. CO_2 Polymer Membranes

Researchers have found that CO_2 can be more soluble than other common gases (water vapor, nitrogen) in certain polymer membranes. The research focuses on assessing how fast CO_2 can flow through the membrane, and how selective the membrane can be in separating CO_2 from other gases. The researchers designed a layered membrane that is both ultra-selective and ultra-permeable. They used a bottom layer of porous polyacrylonitrile that acts as a physical support for the middle layer of either elastomer-like polydimethylsiloxane or glassy-type polytetrafluoroethylene.[11] A patchy layer of polyaminen selectively attracts carbon dioxide, pulling it into the membrane and leading to much higher separation from nitrogen, water vapor, oxygen, and other ambient gases.[11] The high solubility mechanism enhances the concentration of CO_2 in the surface layer, consequently, a highly permeable with low selectivity membrane is placed next to the soluble surface layer, which allows for fast flow of CO_2 gas in comparison to other gases.[11] The developed method is economical and easy to assemble.

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