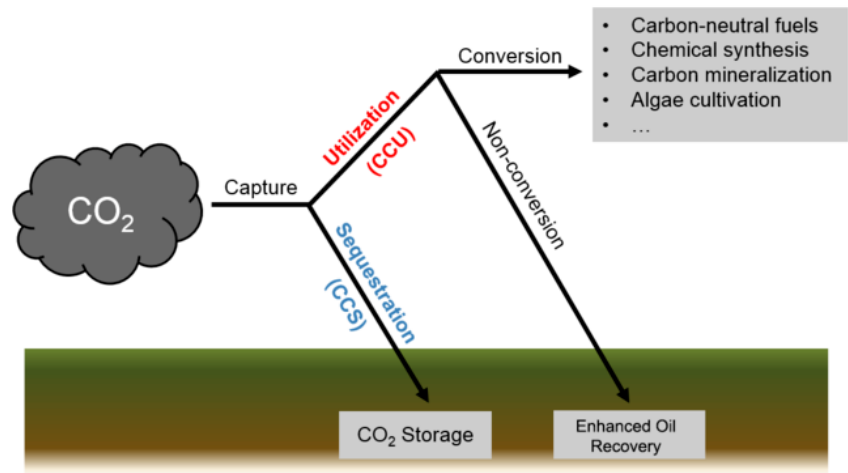




Carbon capture and utilization

Carbon capture and utilization (CCU) is the process of capturing carbon dioxide (CO₂) to be recycled for further usage.^[1] Carbon capture and utilization may offer a response to the global challenge of significantly reducing greenhouse gas emissions from major stationary (industrial) emitters.^[2]

CCU differs from *carbon capture and storage* (CCS) in that CCU does not aim nor result in permanent geological storage of carbon dioxide. Instead, CCU aims to convert the captured carbon dioxide into more valuable substances or products; such as plastics, concrete or efuel; while retaining the carbon neutrality of the production processes. CCU and CCS are sometimes discussed collectively as *carbon capture, utilization, and sequestration* (CCUS).



Comparison between sequestration and utilization of captured carbon dioxide

Captured CO₂ can be converted to several products: one group being alcohols, such as methanol, to use as efuels and other alternative and renewable sources of energy. Other commercial products include plastics, concrete and reactants for various chemical synthesis.^[3]

Although CCU does not result in a net carbon positive to the atmosphere, there are several important considerations to be taken into account. As CO₂ is a thermodynamically stable form of carbon, manufacturing products from it is energy intensive.^[4] The availability of other raw materials to create a product should also be considered before investing in CCU.

Considering the different potential options for capture and utilization, research suggests that those involving chemicals, fuels and microalgae have limited potential for CO₂ removal, while those that involve construction materials and agricultural use can be more effective.^[5]

The profitability of CCU depends partly on the carbon price of CO₂ being released into the atmosphere.

Sources of carbon

CO₂ is typically captured from fixed point sources in heavy industry such as petrochemical plants.^[6] CO₂ captured from these exhaust stream itself varies in concentration. A typical coal power plant will

have 10-12% CO₂ concentration in its flue gas exhaust stream.^[7] A biofuel refinery produces a high purity (99%) of CO₂ with small amount of impurities such as water and ethanol.^[7] The separation process itself can be performed through separation processes such as absorption, adsorption, or membranes.^[8]

Another possible source of capture in CCU process involves the use of plantation. The idea originates from the observation in the Keeling curve that the CO₂ level in the atmosphere undergoes annual variation of approximately 5 ppm (parts per million), which is attributed to the seasonal change of vegetation and difference in land mass between the northern and southern hemisphere.^{[9][10]} However, the CO₂ sequestered by the plants will be returned to the atmosphere when the plants die. Thus, it is proposed to plant crops with C4 photosynthesis, given its rapid growth and high carbon capture rate, and then to process the biomass for applications such as biochar that will be stored in the soil permanently.^[11]

Examples of technology and application

CO₂ electrolysis

CO₂ electroreduction to a variety of value-added products has been under development for many years. Some major targets are formate, oxalate, and methanol, as electrochemical formation of these products from CO₂ would constitute a very environmentally sustainable practice.^[12] For example, CO₂ can be captured and converted to carbon-neutral fuels in an aqueous catalysis process.^{[13][14]} It is possible to convert CO₂ in this way directly to ethanol, which can then be upgraded to gasoline and jet fuel.^{[15][16]}

Carbon-neutral fuel

A carbon-neutral fuel can be synthesized by using the captured CO₂ from the atmosphere as the main hydrocarbon source. The fuel is then combusted and CO₂, as the byproduct of the combustion process, is released back into the air. In this process, there is no net carbon dioxide released or removed from the atmosphere, hence the name carbon-neutral fuel.

Methanol fuel

A proven process to produce a hydrocarbon is to make methanol. Traditionally, methanol is produced from natural gas.^[17] Methanol is easily synthesized from CO₂ and H₂. Based on this fact the idea of a methanol economy was born.

Methanol, or methyl alcohol, is the simplest member of the family of alcohol organic compound with a chemical formula of CH₃OH. Methanol fuel can be manufactured using the captured carbon dioxide while performing the production with renewable energy. Consequently, methanol fuel has been considered as an alternative to fossil fuels in power generation for achieving a carbon-neutral sustainability.^{[18][19]} Synthesis of methanol from carbon dioxide is done through a hydrogenation reaction in the presence of a catalyst. Commonly used catalysts are copper, zinc, and palladium. These reactions are typically performed under high pressure conditions to shift the reaction equilibrium towards the methanol product via Le Chatelier's Principle.^[20] Carbon Recycling International, a company with production facility in Grindavik, Iceland, markets such Emission-to-

Liquid renewable high octane methanol fuel with current 4,000 tonne/year production capacity.^[21]

Dimethyl Ether

Dimethyl Ether has shown promise as a carbon neutral fuel as a potential alternative to diesel fuel. Dimethyl Ether is typically synthesized from a dehydration reaction of methanol in the presence of an acid catalyst, but researchers have recently developed a one step method to convert carbon dioxide into dimethyl ether using a bifunctional catalyst and similar conditions to the synthesis of methanol from syngas.^[22]

Chemical synthesis

As a highly desirable C₁ (one-carbon) chemical feedstock, CO₂ captured previously can be converted to a diverse range of products. Some of these products include: polycarbonates (via Zinc based catalyst) or other organic products such as acetic acid,^[23] urea,^[23] and PVC.^[24] Currently 75% (112 million tons) of urea production, 2% (2 million tons) of methanol production, 43% (30 thousand tons) of salicylic acid production, and 50% (40 thousand tons) of cyclic carbonates production utilize CO₂ as a feedstock.^[25] Chemical synthesis is not a permanent storage/utilization of CO₂, as aliphatic (straight chain) compounds may degrade and release CO₂ back to the atmosphere as early as 6 months.^[24] As the use of fossil fuels decreases, removing carbon dioxide from the air is increasingly seen as a way to stop the long-term accumulation of greenhouse gases in the atmosphere. Carbon emissions and storage coupled with reductions in fossil fuel use are known as "negative emissions".

Carbon dioxide also could be used in chemoenzymatic processes to synthesize starch without cells. In nature starch is usually synthesized within cells from carbon dioxide via photosynthesis. In cell-free synthesis, carbon dioxide is reduced to methanol with an inorganic catalyst; then methanol is converted to three carbon sugar units. The three carbon sugar units will be converted to six carbon sugar units and finally polymerize into starch. Compared to photosynthesis, which involves sixty biochemical reactions, cell-free synthesis needs eleven steps. This means cell-free synthesis can be faster than photosynthesis. The synthesis rate is 8.5 times that of corn starch, and the absorbance rate of carbon dioxide is more efficient than that of plants.^[26] This method is still developing, and the first publication on the topic was only in 2021, so there are still some problems. First, this method needs significant energy inputs, just as plants need sunlight. If the electricity used is not produced cleanly, large carbon dioxide emissions will still result. Moreover, high costs present a barrier to commercialization.

In 2023, an international team of researchers at the University of Sydney and the University of Toronto developed a new acid-based electrochemical process for the conversion of CO₂ captured from emission sources or directly from air.^[27]

Enhanced oil recovery (EOR)

In EOR, the captured CO₂ is injected into depleted oil fields with the goal to increase the amount of oil to be extracted by the wells. This method is proven to increase oil output by 5-40%.^[24]

Enhanced gas recovery (EGR)

Carbon Sequestration with Enhanced Gas Recovery (CSEGR) is a process in which CO₂ is injected

deep in the gas reservoir and as a result, at the gas wells which are some distance away, methane (CH_4) is produced. This process by active injection of CO_2 causes repressurization and methane displacement, so that the gas recovery becomes enhanced compared to water-drive or depletion-drive operations.^[28]

Carbon mineralization

Carbon dioxide from sources such as flue gas are reacted with minerals such as magnesium oxide and calcium oxide to form stable solid carbonates. These minerals can be mined, or existing brine and waste industrial minerals (including slag) can be reused.^[29] The carbonates produced can be used for construction, consumer products, and as an alternative for carbon capture and sequestration (CCS).

Approximately 1 tonne of CO_2 is removed from the air for every 3.7 tonnes of mineral carbonate produced.^[29]

Biofuel from microalgae

A study has suggested that microalgae can be used as an alternative source of energy.^[30] A pond of microalgae is fed with a source of carbon dioxide such as flue gas, and the microalgae is then allowed to proliferate. The algae is then harvested and the biomass obtained is then converted to biofuel. About 1.8 tonnes of CO_2 can be removed from the air per 1 tonne of dry algal biomass produced, though this number actually varies depending on the species.^[31] The CO_2 captured will be stored non-permanently as the biofuel produced will then be combusted and the CO_2 will be released back into the air. However, the CO_2 released was first captured from the atmosphere and releasing it back into the air makes the fuel a carbon-neutral fuel. Microalgae biofuels are considered to be apart of the third generation of biofuels, being an alternative energy source for fossil fuels without the disadvantages accompanying first and second generation biofuels.^[32] This technology is not mature yet.^[33] Current microalgal culture systems have not been designed for high throughput biomass growth and carbon capture. Raceways, high-rate algal ponds, and photobioreactors are the most widely used for microalgal cultivation at a large-scale. The limitations of these systems are related to microalgal growth requirements. Ponds are operated at narrow depth to ensure sufficient light distribution and thus need a large land surface.^[34]



Fuels can be produced from algae

Agriculture

An approach that is also proposed as a climate change mitigation effort is to perform plant-based carbon capture.^[35] The resulting biomass can then be used for fuel, while the biochar byproduct is then utilized for applications in agriculture as soil-enhancer. Cool Planet (<https://www.coolplanet.com>) is a private company with an R&D plant in Camarillo, California, performed development of biochar for agricultural applications and claimed that their product can increase crops yield by 12.3% and three-fold return of investment via improvement of soil health and nutrient retention.^[36] However, the claims on the efficacy of plant-based carbon capture for climate change mitigation has received a fair amount of skepticism.^[37]

Environmental impacts

16 life cycle environmental impact analyses have been done to assess the impacts of four main CCU technologies against conventional CCS: Chemical synthesis, carbon mineralization, biodiesel production, as well as Enhanced Oil Recovery (EOR). These technologies were assessed based on 10 Life-cycle assessment (LCA) impacts such as: acidification potential, eutrophication potential, global warming potential, and ozone depletion potential. The conclusion from the 16 different models was that chemical synthesis has the highest global warming potential (216 times that of CCS) while enhanced oil recovery has the least global warming potential (1.8 times that of CCS).^[1]

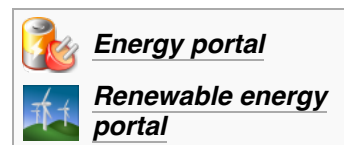


Sites of Carbon Capture and Utilization projects and development, per 2011 report from Global CCS Institute.^[38]

Life-cycle assessments (LCA) are not standardized as studies that perform them use different assessment methodologies and parameter that change the results of the LCA. Enhanced methodology guidelines and standardization of practice are necessary to better gauge and compare the impact of the various CCU technologies.^[39]

See also

- Carbon capture and storage
- Carbon neutral fuel
- Carbon sequestration
- Climate change mitigation
- Greenhouse gas removal
- List of energy topics
- Low-carbon economy
- Solar Foods Ltd.



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Further reading

- *Introduction to Carbon Capture and Sequestration*. The Berkeley Lectures on Energy. Vol. 1. 2014. doi:10.1142/p911 (<https://doi.org/10.1142%2Fp911>). ISBN 978-1-78326-327-1.
- Novel carbon capture and utilisation technologies: Research and climate aspects Berlin: SAPEA. *Science Advice for Policy by European Academies* (Report). 2018. doi:10.26356/CARBONCAPTURE (<https://doi.org/10.26356%2FCARBONCAPTURE>).
- New route to carbon-neutral fuels from carbon dioxide discovered by Stanford-DTU team (<https://www.dtu.dk/english/news/2019/09/new-route-to-carbon-neutral-fuels-from-carbon-dioxide-discovered-by-stanford-dtu-team?id=4feafcd3-bf1d-4e02-80ea-ea018bfc6caf>)

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