Group K
Gracey, Joey, Jay, Shea, Min, Yumin

Carbon Capture Strategies

Carbon dioxide is a chemical compound composed of one carbon and two oxygen atoms. It is released out of all living things such as humans and animals as they expire air in a process called respiration. Carbon comes from fossil fuels and is released into the atmosphere when the fuels are burned. Carbon dioxide contributes to global warming and environmental hazards that are articulated in the article "Are the effects of global warming really that bad?" (M.Denchak). It demonstrates the various ways global warming and carbon dioxide can cause environmental hazards. There is an increasing number of severe weather conditions including storms, droughts in hot areas, floods and heat waves. There is more polluted air which is caused by the rising temperatures that raise the ground level ozone which transforms into air pollution from cars, factories and other sources of pollution. Another example would be the higher wildlife extinction rate which is resulted from hot areas without water, natural disasters and climate change.

In the article "News" (Marine pollution bulletin, pg.156), they state, "that the Arctic ice, the polar bear's primary habitat, is melting much faster than previously thought…there are about 15,000 polar bears in northern Canada, accounting for about two-thirds of the world's total population". The Arctic is where the polar bears survive and as the ice melts due to rising warm temperatures, they are becoming closer to extinction at a higher rate.

Furthermore, as written in "Geographic proximity and public acceptance of carbon capture and storage facilities" (M.Krause), carbon capture and storage is an approach to mitigate climate change by capturing carbon dioxide emissions and injecting and storing it in an underground geological formation. This is a positive alternative as it removes carbon dioxide from the atmosphere and attempts to inject it deep underground, so it does not escape. They transport the compressed carbon dioxide by pipeline to storage sites and inject it underground reducing greenhouse gases that are released into the atmosphere. Due to the depths, compressed carbon dioxide stays pressurized therefore preventing the majority of the gas from rising back into the earth's atmosphere.

Continuing on, some methods of carbon capture are Oxyfuels combustions which fossil fuels are burned in oxygen rather than the air and atmosphere. There is a process to capture carbon dioxide when it comes to Oxyfuels and benefits/drawbacks that will be discussed. Another method is using Microalgae which efficiently uses inorganic carbon to produce oxygen and many other useful products. In addition, microporous organic polymer is a chemical structure that contains a pore less than 2nm in diameter and it can be used to absorb carbon dioxide. In a process called solar thermal electrochemical photo (STEP) sunlight captures and concentrates and allows carbon dioxide to be captured through electrolysis cells. And finally, silicate weathering attempts to control climate change by consuming atmospheric carbon dioxide in geological scales. In this paper, we will discuss the advantages and disadvantages of these methods of carbon capture and how they function and fight to keep the environment clean and safe.

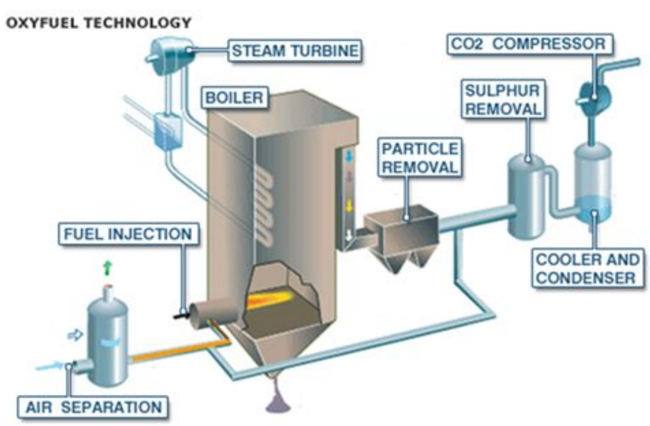


Figure 1. Shows the process of Oxy-fuel technology. Retrieved from www.icb.csic.es

Carbon Capture and Storage first began in the 1920s as separation methods of gases. In 1977 Texas, U.S.A, it was considered as a new technology (IEA). The first steps in Carbon Capture and Storage using oxy-fuel involves capturing carbon dioxide emissions that are released from fossil fuels being burned. Oxy-fuel combustion involves the process of isolating oxygen from air with the fuel component being combusted in oxygen. To dilute the product, flue gas (recycled) is used (Adams 2010). Oxy-fuel combustion uses flue gas that contains carbon dioxide and water. It may also contain oxygen, SOx, NOx, hydrochloric acid and mercury in the gas stream. Condensation and after cooling processes of the flue gas is necessary before the transportation and storage of the gas stream. Once the carbon dioxide is at a state of adequate purity it is ready for storage. Many processes are still being developed in increasing the pureness of the carbon dioxide that is made from combustion of oxy-fuel (Adams 2010). Additional methods can also be used for carbon capture: pre- and post-combustion capture (CCSA 2020).

The benefit of Carbon Capture and Storage is that it moves towards finding a climate change solution. Additionally, tackling climate change in an affordable and economic way. Using this technology would decrease global carbon dioxide emissions by 19% by 2050. Therefore, in the ecological and economical perspectives, less money would have to be put into managing climate change and using carbon capture is also very cost affordable. Without Carbon Capture and Storage, the fight against climate change would be much more expensive (70% more), according to CCSA Association (2020). Fuel plants using Carbon Capture and Storage have some advantages over using nuclear and renewables. For instance, capturing carbon can keep a balanced energy supply and can deal with increasing rates in demand of supply. Many nuclear and renewable energy sources cannot sustain this demand. Using Carbon Capture and Storage can create a low carbon environment not only in fossil fuel industries; but also, in industries producing cement, steel or chemicals. Another form of carbon capture that can create a positive change is capturing the carbon dioxide emissions that are released when plants are burned. This will extensively reduce the amount of carbon dioxide in the atmosphere. This is because plants absorb a high amount of carbon dioxide from the air and act as carbon sinks. Carbon Capture and Storage would be a great solution in ensuring the burning of plants will not destroy these carbon sinks while these plants are still used for producing power. However, there are some disadvantages to this form of technology. When biomass is mixed with Carbon Capture and Storage products, undesirable carbon dioxide emissions can be produced in the environment (CCSA 2020). Additionally, this process still produces carbon dioxide during combustion. According to Climate Vision, some of this carbon dioxide is leaked from the storage sites or from pipelines (2015). Other harmful by-products are produced as well as carbon dioxide; for example, nitrogen. Over time, the release of carbon dioxide may exceed the storing of carbon dioxide using oxy-fuel combustion. According to Zactruba at bright hub engineering, oxy-fuel can be a very energy extensive process (2020). Therefore, the costs may be greater than the benefits. There are many detrimental effects of carbon dioxide pollution on the environmental ecosystems and the health of the human population. This is why it is essential to select the correct storing sites and ensure proper maintenance of those sites (2015).

Using oxy-fuel as a way of Carbon Capture and Storage is sustainable and economically friendly. The cost is affordable and helps to reduce carbon energy supplies and the amount of carbon dioxide in the atmosphere. More specifically, world-wide there would be a 70% increase in carbon dioxide emissions without Carbon Capture and Storage (CCSA 2020). It would cost approximately fifty to seventy Canadian dollars per tonne of carbon dioxide for one project. The projects involving carbon capture were much higher in cost but that has recently declined. This process can also be made cheaper by using other forms of industrial processes. By using these already existing methods; the pure carbon dioxide stream can be moved to close storage sites which will also lower the cost in transportation (CCSA 2020). An example of a plant that already produces these carbon dioxide emissions are natural gas plants. This is a very environmentally reusable approach and a good way to reduce the cost of separating the compounds. However, there are also some economic drawbacks in the uses of oxy-fuel. The transportation of the product to the storage site and the heat transfer step in combustion are very energy extensive and not economical (Zactruba, 2020).

Fossil fuel plants that produce power can work towards building the plants with carbon capture opportunities in place. Therefore, the carbon capture process can be ready and no transportation will be needed from the plant site. In having the carbon capture and storage right on site, the cost and the environmental footprint will be reduced. There are also technologies being produced to enhance the efficiency of oxy-fuel combustion and carbon capture and storage processes. The ion-transport membrane (ITM) technology is an example (Carpenter et al. 2017). This process could possibly bring higher carbon dioxide purities without the extra inefficient energy needed (like in oxy-fuel combustion). An additional option for relieving the carbon dioxide storage sites of their supply is the employ microalgae, an organism which uses large concentrations of carbon dioxide for growth. (Microalgae).

Microalgae are unicellular organisms which are capable of photosynthesis. They are important as they produce about half the atmospheric oxygen on earth while using carbon dioxide (CO_2) for growth (Microalgae). Typically, carbon sequestration is costly and energy expensive but using microalga remediation may prove to be an efficient and cost-effective method. There are many advantages to using microalgae for carbon capture. First, microalgae grow very quickly even in non-arable soil with non-potable water. Second, microalgae can also grow in diverse environments which may be constantly changing. Microalgae also carry-out CO_2-fixation while producing other products which can be of use in other fields. For example, the entire biomass of microalgae can be harvested for agricultural fertilizer, nutritional supplements and fish food. This strategy releases zero waste products if feasible. (Thomas, Mechery and Paulose).

For optimal growth microalga require nutrients and solar radiation as well as enough CO_2. Flue gases (exhaust gases from fireplaces, ovens, furnaces, boilers, steam generators etc.), however, have a sufficient concentration of feed CO_2 to support the growth of microalgae which could help to reduce CO_2 from storage sites. Partnering with projects which remove and purify flue gases decreases the overall cost of employing microalgae as a carbon remediation tool. There are approximately 25,000 thermal power plants across the world. Medium-sized plants produce 11,400 megatons of CO_2 /day. It would take ~32,837 hectares of land to produce the biomass of algae necessary to sequester that amount of CO_2 as this process would take place in an industrial size photobioreactor. A photobioreactor is a system which mixes nutrient medium, microalgae and gaseous CO_2 to grow microalgae biomass via photosynthesis. Because power plants do not have space for microalgae photoreactors, the CO_2 gases would need to be captured and transported to photoreactors sites. There are some advantages to compression and transport of CO_2. Compression and transport of CO_2 was priced at $11.78 for 100km but used ~27 MW of electricity (Thomas, Mechery and Paulose). This energy usage may outway the benefits of the carbon sequester. Through compression maybe be costly it is a widely researched method for CO_2 sequestration, one example is using Microporous Organic Polymers (MOPs).

Microporous Organic Polymers (MOPs), is a newly founded method proposed for carbon capture. Inorder for us to understand this MOPs strategy, we need to know what polymer and micropores are. Polymerization in chemistry is mainly focused on the synthesis and structure of chemical bonds. The general description of a polymer is a molecule created by many repeated units. And by changing the structure or synthesis of elements. There are many different chemical structures that come with different chemical properties. Microporous is a material that has space inside the material, also known as a pore, which the diameter is less than 2 nanometer size (Robert *et al. 2011*). Therefore, Microporous Organic Polymer is a type of polymer that contains repeated units with tiny spaces which can be used to store particles.

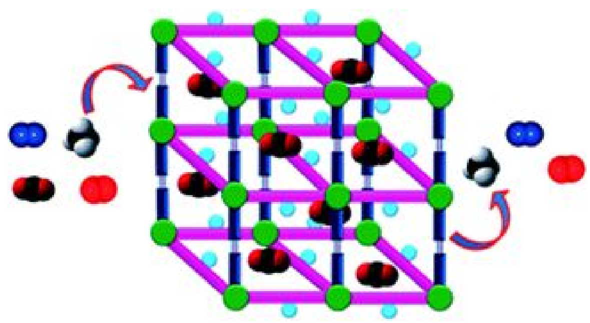


Figure 2. Graphical Abstract of Porous coordination polymers

Scientists focused on this tiny space inside the polymer to store CO_2 waste. Figure 2 is a simple picture of porous coordination polymers, used for carbon capture and the general mechanism is similar to MOPs. Inside the polymer, the pore is filled with CO_2 gas (two red atoms refer to hydrogen and one black atom refer to oxygen in the image).

In order to capture the CO_2 gas, it needs to be in the post-combustion status. According to the Royal Society of Chemistry journal article, ‘Microporous organic polymers for carbon dioxide capture’, scientists experimented on seven different MOPs samples and observed the amount of CO_2 isotherms absorption (Robert *et al. 2011*).

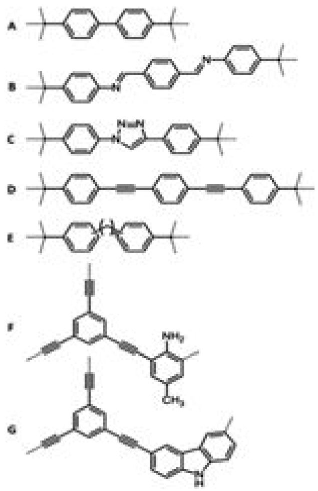
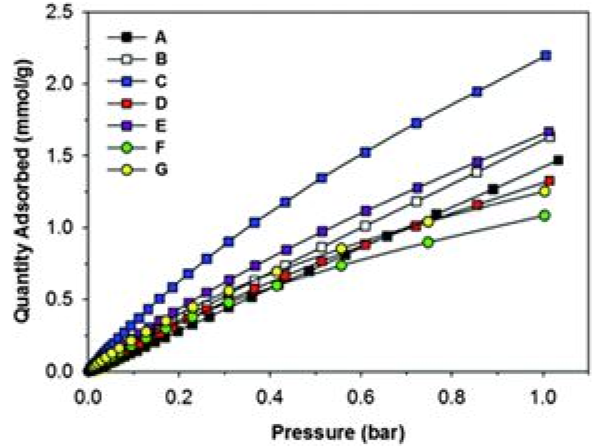


Figure 3- Samples of different types of MOP structures. (Left)

Figure 4- Graph of samples show quantity CO_2 adsorbed at varying pressures. (Right)



Based on the data from figure 3, sample C was synthesized with tetrakis (4-azidophenyl) methane and tetrakis (4-ethynylphenyl) methane via a reaction call “click” and has the highest sample of CO_2 uptake out of different MOPs (Robert *et al. 2011*). Under the same condition of maximum pressure (1 bar) with temperatures of 273 to 298 K, the most efficient MOPs sample C had an uptake of 3.86 MMOL /g of CO_2 at 273 K and 2.20 MMOL/g at 298 K degree (Robert *et al. 2011*). However, sample C does not have the largest volume of surface area (1237m^2/g) (Robert *et al. 2011*). This experiment shows that based on the MOPs structure; sample C has a high potential of growing efficiency levels.

Moreover, MOPs for capturing CO_2 have high stability if based on the chemistry and physics under the post – combustion condition in the right range of temperature and pressure (Robert *et al. 2011*). But the MOPs method still faces a few problems to overcome. It has two main issues, which are budget and the absorbent rate. Especially, as we can see in Figure3 and 4, absorbent rate is the main challenge. Further research is needed inorder for us to increase the absorbency rate of a new MOPs structure. Though sample C had one of the highest absorbance rates of 2.20 MMOL/g to 3.86 MMOL/g, this is still not efficient enough and not ready for use. Further research and experimentation into new MOPs could discover new ways of managing CO_2 gas emissions in the future. In terms of future technology, there are different approaches to CO_2 sequestration, which lowers the cost of the operational energy by using naturally driven energy, such as sunlight, which lead us to an introduction of STEP (Solar Thermal Electrochemical Production/Photo) process.

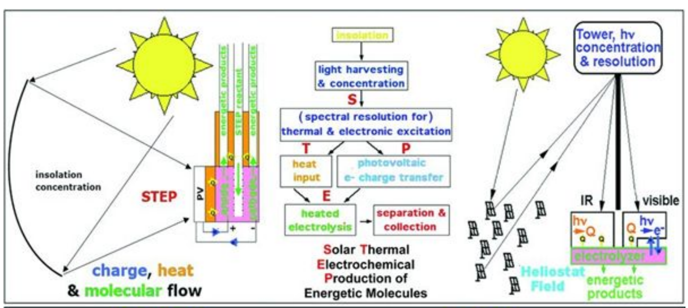
Solar Thermal Electrochemical Production/Photo (aka STEP) is an endothermic process that utilizes sunlight energy to drive photovoltaic charge transfer, and it enables usage of rest of the remaining sunlight energy to decrease the energy requirement for electrolysis reaction. Theory of STEP was introduced in 2009 as an extension of an earlier solar water splitting process. (Wang, Baohui, et al. 2012) STEP chemistry includes two aspects, improved solar utilization by increasing solar conversion efficiency and management of thermodynamics and kinetics of the chemical reaction. Three efficiencies are involved in using STEP, which are 1) Drive the entire reaction by solar energy without any help of other energy source, 2) Matching the range of solar spectrum and coupling solar to thermal and solar to electricity conversion, and 3) Balancing the photochemical, thermochemistry and electrochemistry of the reaction. STEP chemistry has been proven useful for treatment of iron, ammonia, wastewater, organic synthesis, and now it has been proposed to capture CO_2. Important aspect of STEP is that it can perform carbon capture in a single step compared to other carbon capture methods.

For the first step of the process, sunlight has been captured and concentrated.hile solar energy can be stored externally in liquid form. CO_2 is captured using an electrolysis cell, that has been powered by sunlight energy, which can be transferred to undergo endothermic conversion of carbon dioxide. The electrolysis process has been enhanced due to the decreased thermal energy requirement by increasing the temperature using external heat. Solar visible energy creates electronic charge to drive electrolysis, then CO_2 gets to be captured as solid carbon form that can be stored or used in synthetic oil production. (Licht, Stuart, et al, 2011)

Energy requirement of the chemical reaction has been solved by how the process utilizes solar thermal heating during the electrolysis. The process applies Solar thermal heating as an external heat during the separation of CO from molten lithium carbonate electrolyte, which causes the free energy (ΔG) and electrolysis potential to decrease, which allows the reaction to go endothermic.

Unlike other processes, STEP focuses mainly on the redox potential to match the bandgap than the energy matching the electrolysis potential. As we can see in figure 6, the STEP process has a high temperature pathway decreasing the thermodynamic energy requirement, with the distinguished radiation, that is intrinsically energy efficient compared to other processes such as Multi-PV and Ambient temperature solar driven electrolysis. The electron separation and electronic charge transfer driven by bandgap energy occurs in photovoltaic. **(**Licht, Stuart, et al. 2010) Then the sub bandgap (intrinsically energy insufficient) excess radiation transfer heat to warm up the electrolysis chamber. Sequentially, Low energy electrolysis is performed using high heat, which then creates energy rich products, and the cycle is completed by preheating the electrolysis reactant through heat exchange between energetic product and reactant. Result of the process is the production of CO(s) which can be used for bulk manufacturing of acetic acid and aldehyde. (which are used as industrial gas myriad)

Current situation of maintaining solar efficiency of this process is incomplete, it is currently about 37% solar efficient, which leaves 63% of isolation not utilized as a heat source. Also part of the problem is the stability of the materials and electrocatalysts, which can have a varied range of outcome in terms of efficiency. (Licht, S. 2011)



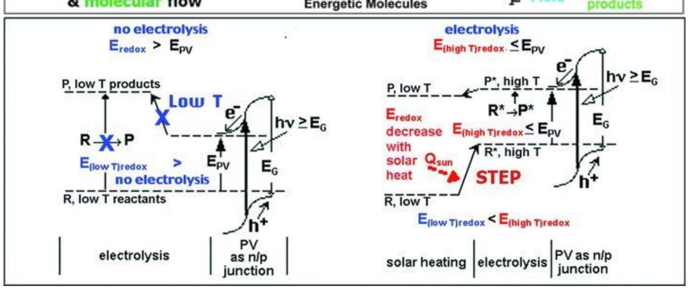


Figure 5. Overall flow of STEP process **(**Licht, Stuart, et al. 2010)

Figure 6. Graph describing the usage of high temperature to change thermodynamic requirement of endothermic reaction (Licht, S. 2011)

Thus far, there are many methods which have been proposed for carbon capture sequestration, all of which have their benefits and drawbacks. Potentially, the feasibility of some of these methods may increase by combining a few of the most efficient strategies. The uncertainty lies in the decision between which methods holds the largest carbon sequestering power without causing additional harm. The final strategy proposes chemical silicate weathering as a strategy for carbon capture but not without the unsettling possibility of harmful chemical interactions and ecosystem disruption.

Carbon capture via silicate weathering is a well documented phenomenon. The equation by which it draws down CO_2 is as follows (this is a simplified equation for a specific mineral; however many other minerals exist which have the same function): $\mathbf{CaSiO_3 + 2CO_2 + 3H_2O \leftrightarrow Ca^{2+} + 2HCO_3^- + H_4SiO_4}$**.** It is apparent from looking at the equation that this mechanism is an effective drawdown of CO_2, but just how effective is it? Could this be a potential climate saver if we somehow engineer an artificial process to mimic this, or some way to kickstart a large-scale weathering event somewhere on earth?

In Earth's history, there have been a handful of large basaltic eruptions called large igneous provinces (LIP's) which have changed the climate at the time of eruption drastically. This is due to basaltic rocks being much more weatherable than more granitic rocks due to their mineral compositions. These LIP's have two effects on the atmospheric CO_2, the first being an immediate increase as the volcanic eruption outgasses CO_2 to the atmosphere, and the second being the drawdown of CO_2 as the LIP weathers. If these LIP's are emplaced in low latitude areas, where weathering is high, their potential for climate change is immense, as outlined by the research done by Lefebvre *et al.* (2010). Lefebvre *et al.* analyzed the Hirnantian cooling event, which was preceded by a warming event, and occurred during the late Ordovician. This warming event, rapidly followed by glacial conditions closely resembles the result of a LIP being emplaced in a low latitude area, followed by extreme weathering, and upon further analysis of Sr isotopes, high sea level, and extensive black shales, Lefebvre *et al.* (2010) conclude that it is extremely likely that a LIP was the cause of the Hirnantian cooling event. Other LIP's throughout history have had similar effects, such as the Deccan and Siberian traps. This shows the potential for climate change due to weathering of silicate rocks given a large enough scale.

In total, the amount of silicate weathering in the world currently can be estimated. Dessert *et al.* (2010) estimated the total flux of CO_2 from atmospheric reservoir to the rock reservoir by measuring river runoff using the equation: $f_{CO2} = R_f*323.44\exp(0.0642*T)$ where f_{CO2} is the specific atmospheric consumption rate of CO_2 (mol/km^2/yr), R_f is the runoff (mm/yr) and T is the temperature (ºC). Using digitised maps of mean annual runoff and temperature,

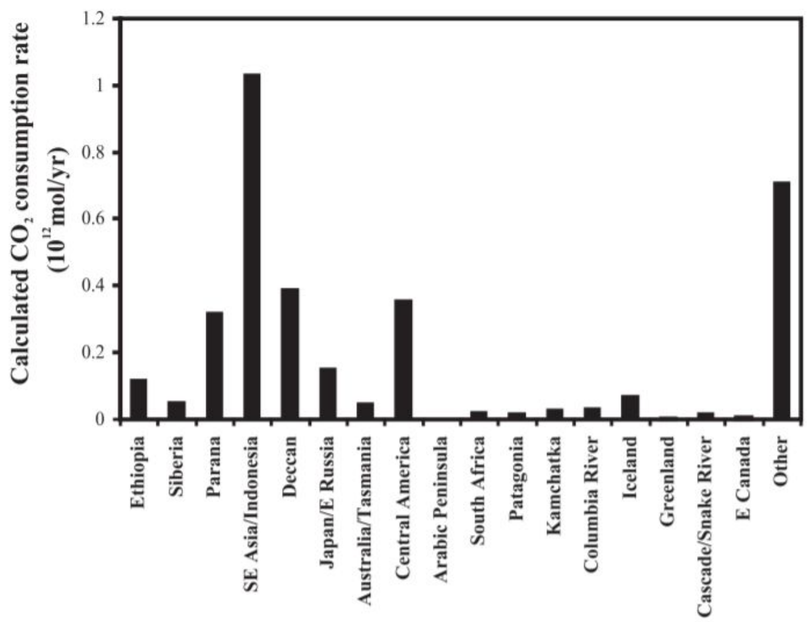


Figure 7. Annual CO_2 Consumption rate based on geographic area (Dessert et al., 2003).

Dessert *et al.* have compiled CO_2 fluxes from different basaltic sources around the world, as shown in figure 7 above. In total, the CO_2 consumption for all sites, is about $3.11*10^{12}$ mols/yr (Dessert *et al.*, 2003) or ~0.15 petagrams, which is a relatively significant number when we consider the amount of CO_2 produced by humans is around 500 petagrams (10^{15} grams). If this process can be sped up, or artificially enhanced, it is a carbon sink worth looking into.

How can we make this weathering draw down more effective? A possibility for our climates future could be in the hands of geoengineers, who are looking into solutions for the rising levels of CO_2, by artificially increasing the rate of silicate weathering. Köhler *et al.* (2010)

are looking into increasing the amount of silicate weathering by distributing a fine olivine powder throughout the Congo and Amazon rainforests. Between these two areas, Köhler *et al.* (2010) estimate that this method could sequester about 5 petagrams of CO_2 per year, which is a very large number, considering all that is needed for this method is the distribution of a fine dust into rivers in hot places. An issue with this method however, is that the dissolution of such large amounts of olivine in isolated places may increase the pH and alkalinity of the rivers and disrupt the local ecosystems, as well as the olivine having the need to be spread out so the water does not reach its saturation limit with regards to silicic acid, which is created in the reaction (Köhler *et al.*, 2010). Another issue with the method is that in areas such as the Amazon, it may be difficult to distribute a powder effectively in large quantities, as the preferred method would be aerially, however with the forest cover in the Amazon, not all the powder would reach the desired targets. Hartmann *et al.* (2013) suggest that adding olivine dust to the ocean could further increase the CO_2 drawdown effect, but due to the complexity of the oceanic ecosystem and chemical interactions, more research is needed.

In terms of possibly enhancing CO_2 drawdown by silicate weathering, olivine dust distribution seems to be the ideal plan, as the breakdown of olivine will, in addition to sequestering CO_2, combat ocean acidification by increasing alkalinity (Hartmann *et al.*, 2013). Both of those things are excellent, however the potential chemical interactions and disruption of ecosystems are negatives that must be understood before any actions can be taken. The potential of this drawdown is obvious based on previous evidence, however potential unknowns must be understood before we can take advantage of silicate weathering's potential.

The effects and impacts of carbon dioxide are rising temperatures in the atmosphere, air pollution, wildlife extinction and severe weather conditions, all of which threaten the environment, humans and animals that inhabit the planet. Carbon capture and storage is necessary to reduce carbon dioxide emissions to the atmosphere. The methods discussed in this article demonstrate the plethora of options as well as the urgency to find solutions to the issue.

The first method discussed is Oxy fuel as a form of carbon capture which includes separation of CO2 from flue gases of industrial plants which are major contributors of carbon dioxide output. The disadvantages of oxyfuels are the transport of the CO2 product to storage sites and the heat transfer in combustion are very energy extensive and not economical. Microalgae may be useful for decreasing the need for CO2 storage as they are able to use CO2 to produce oxygen and by products useful in many industries. However, these cultures of microalgae would need to be very large to process the amount of CO2 necessary to produce noticeable change. The next a more recently developed strategy uses Microporous Organic Polymers (MOPs), a microporous material with a pore that is less than 2 nanometer in size to store carbon dioxide. However, these pores are too small to sequester a meaningful amount of carbon dioxide so there must need further development to make this strategy more feasible. The newly developed method is STEP chemistry which improves solar utilization by increased solar conversion efficiency and treats iron, ammonia and wastewater treatment and captures carbon dioxide. The problem with solar efficiency is it is not fully complete; it is only 37% solar efficient. And lastly, chemical silicate weathering controls climate change by consuming carbon dioxide. Large igneous provinces (LIP) affect the atmosphere and climate in two ways; one is an increase outgassed of carbon dioxide to the atmosphere; the second effect is carbon dioxide is reduced as the LIP weathers. This has a large negative impact on climate by releasing CO2. This method seems promising but it is uncertain whether adverse chemical interactions may occur in the ecosystems. All in all, carbon dioxide causes numerous environmental issues but there are many methods in carbon capture and storage that attempts to reduce carbon emissions in the atmosphere and sustain a healthier planet.

References

Adams, Deborah. Flue Gas Treatment for CO2 Capture. June. 2010.https://www.usea.org/sites/default/files/062010_Flue%20gas%20treatment%20ffo%20co2%20capture_ccc169.pdf.

"Carbon Dioxide." *ScienceDaily*, ScienceDaily, www.sciencedaily.com/terms/carbon_dioxide.htm.

Carpenter, S. M. & Longlll, H. A. 2017. Integration of carbon capture in IGCC systems. https://www.sciencedirect.com/topics/engineering/oxyfuel-combustion.

Climate Vision. The Negatives of Carbon Capture and Storage. July. 2015. http://climatevision.co.uk/the-negatives-of-carbon-capture-and-storage.

Dawson, Robert, et al. "Microporous Organic Polymers for Carbon Dioxide Capture." *Energy & Environmental Science*, vol. 62, no. 3, Mar. 2013, pp. 345–352., doi:10.1002/pi.4407.

Dessert, Céline, et al. "Basalt weathering laws and the impact of basalt weathering on the global carbon cycle." Chemical Geology 202.3-4 (2003): 257-273.

Denchak, Melissa. "Are the Effects of Global Warming Really That Bad?" *NRDC*, 6 Aug. 2019, www.nrdc.org/stories/are-effects-global-warming-really-bad?gclid=CjwKCAiAhJTyBRAvEiwAln2qB_dAxbwan9vM97Vv1bIIJeK3-o_jJAeSMECUol9NVqaldHsQ2ZtdXRoCoJ0QAvD_BwE.

IEA Greenhouse Gas R&D Program. A Brief History of CCS and Current Status. 2020. https://ieaghg.org/.

Hartmann, Jens, et al. "Enhanced chemical weathering as a geoengineering strategy to reduce atmospheric carbon dioxide, supply nutrients, and mitigate ocean acidification." Reviews of Geophysics 51.2 (2013): 113-149.

Köhler, Peter, Jens Hartmann, and Dieter A. Wolf-Gladrow. "Geoengineering potential of artificially enhanced e weathering of olivine." Proceedings of the National Academy of Sciences 107.47 (2010): 20228-20233.silicat

Krause, Rachel M., et al. "'Not in (or Under) My Backyard': Geographic Proximity and Public Acceptance of Carbon Capture and Storage Facilities." *Risk Analysis*, vol. 34, no. 3, Jan. 2013, pp. 529–540., doi:10.1111/risa.12119.

Lefebvre, Vincent, et al. "Did a Katian large igneous province trigger the Late Ordovician glaciation?: A hypothesis tested with a carbon cycle model." Palaeogeography, Palaeoclimatology, Palaeoecology 296.3-4 (2010): 310-319

Licht, S. "Efficient Solar-Driven Synthesis, Carbon Capture, and Desalinization, STEP: Solar Thermal Electrochemical Production of Fuels, Metals, Bleach." Advanced Materials, vol. 23, no. 47, 2011, pp. 5592-5612.

Licht, Stuart, et al. "Efficient STEP (Solar Thermal Electrochemical Photo) Production of Hydrogen – an Economic Assessment." International Journal of Hydrogen Energy, vol. 35, no. 20, 2010, pp. 10867-10882.

Licht, Stuart, et al. "A New Solar Carbon Capture Process: Solar Thermal Electrochemical Photo (STEP) Carbon Capture." The Journal of Physical Chemistry Letters, vol. 1, no. 15, 2010, pp. 2363-2368.

Licht, Stuart. "STEP (Solar Thermal Electrochemical Photo) Generation of Energetic Molecules: A Solar Chemical Process to End Anthropogenic Global Warming." The Journal of Physical Chemistry C, vol. 113, no. 36, 2009, pp. 16283-16292.

"News." *Marine Pollution Bulletin.* Volume 46, Issue 2,February 2003, Pages 155-158. https://doi.org/10.1016/S0025-326X(03)00019-5

Oxy-fuel Combustion Systems. 2020. www.ccsassociation.org/what-is-ccs/capture/oxy-fuel-combustion-systems/

Singh, et al. "Overview of Carbon Capture Technology: Microalgal Biorefinery Concept and State-of-the-Art." *Frontiers*, Frontiers, 21 Jan. 2019, www.frontiersin.org/articles/10.3389/fmars.2019.00029/full.

Wang, Baohui, et al. "STEP Wastewater Treatment: A Solar Thermal Electrochemical Process for Pollutant Oxidation." Chemsuschem, vol. 5, no. 10, 2012, pp. 2000-2010.

Zactruba, John. 2020. What is Oxyfuel Combustion? https://www.brighthubengineering.com/power-plants/39088-oxy-fuel-combustion-for-co2-capture/.