MONTROSE
ENVIRONMENTAL

Carbon Capture, Sequestration & Conversion

Advanced Net Negative Carbon Conversion Process

Simple & elegant - effective & net-negative.

Montrose Environmental Group (MEG) has developed a simple yet reliable way to remove carbon dioxide from your industrial process. Our process uses a non-toxic, water-based solvent (i.e. not an amine-based or chilled ammonia process) to remove and permanently sequester 99.99% of carbon dioxide (CO_2) from process and combustion exhaust streams. The process produces a carbonate species with resale value and, with the reuse of waste heat and its low parasitic load, provides a negative carbon intensity score. Similar approaches have been attempted in the past but have encountered issues with kinetic and mass transfer limitations. The Montrose Carbon Conversion Process has overcome these barriers with a patented 2-step gas transfer technique. The process allows the removal of CO_2 from influent sources containing CO_2 concentrations ranging from 0.04% - 100% and can be easily scaled up with a relatively small footprint. It is also reliable, easy to operate and sequesters the CO_2 into a stable, valuable product for sale or consumption. This technology (assuming minimum annual thresholds of captured carbon) qualifies for the recently revised and increased 45Q tax credits and direct pay subsidies. If you would like additional information discussing the applicability of this technology to your process, and potentially arranging for an on-site piloting effort, call +1-919-522-2032 or click on the link to receive a white paper providing more information about the novel Montrose Carbon Conversion Process.

The Montrose Carbon Conversion Process may be utilized in direct air capture (DAC) or any other point source emitting CO_2, such as reciprocating internal combustion engines, turbines, or combustion/process sources within a facility. Sources may be collected into a main header or treated directly at point of use.

White Paper:

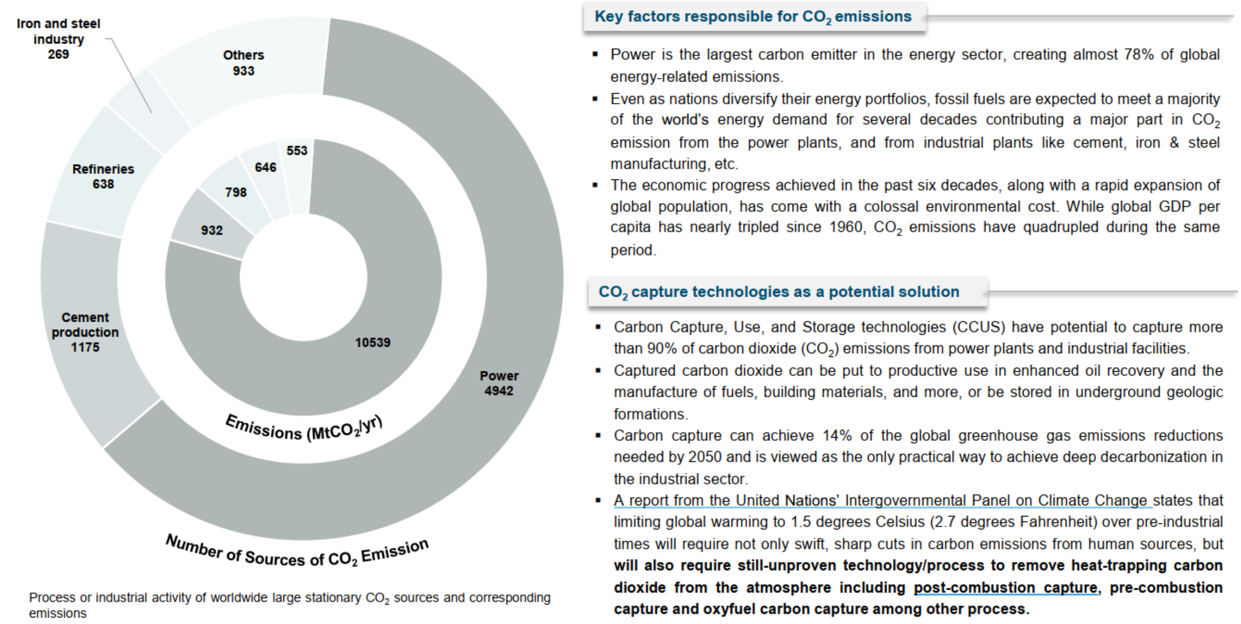
Introduction:

Climate change is one of the most important challenges of our century. It is exacerbated by anthropogenic emissions of greenhouse gases, in particular carbon dioxide (CO_2). Despite increasing public, industrial, and political awareness, CO_2 emissions are projected to increase in the following decades. In this context, carbon capture and storage or sequestration (CCS) has been proposed as an effective near- to mid-term solution to reduce anthropogenic CO_2 impacts. Cost reduction is a major challenge for the CCS technology with the capture step being the most expensive part of the process owing to considerable energy demand (approximately 20–30 % more fuel is needed to achieve the same output of power without CO_2 capture). Next-generation capture technologies offer the potential to improve overall efficiency and reduce the cost of CO_2 capture when compared with current market-leading technologies, i.e., amine-based solvent-scrubbing or ammonia-based pilots and plants. Additionally, technologies without the parasitic energy requirements to strip, compress, refrigerate and/or pump the CO_2 into geologic formations are less complex and therefore easier and faster to deploy around the globe. Ideally, this is accomplished with a net negative carbon budget and a net positive income stream from the generation of a CO_2-sequestering product of value.

There are two main classifications of carbon capture systems that should be addressed in relation to CCS. The first classification is direct air capture (DAC), where ambient concentrations of

CO_2 that have surpassed 421 parts per million by volume (ppmv) (0.04%) as of 2023, are targeted and removed from ambient air. The second classification is point of capture (POC), where large concentrations of CO_2 emitted by a point source are captured. Some POC emissions of CO_2, may be as high as 99+% of the total gas volume, (e.g., fermenters, mining, or chemical processes), while other sources (from combustion processes) have lower percentage level concentrations of CO_2.

There are many POC sources of CO_2 emissions around the globe and targeting removal of certain sources are more impactful than others. A breakdown of carbon sources to the environment is depicted in the following graphic:



Process or industrial activity of worldwide large stationary CO_2 sources and corresponding emissions

Key factors responsible for CO_2 emissions

- Power is the largest carbon emitter in the energy sector, creating almost 78% of global energy-related emissions.
- Even as nations diversify their energy portfolios, fossil fuels are expected to meet a majority of the world's energy demand for several decades contributing a major part in CO_2 emission from the power plants, and from industrial plants like cement, iron & steel manufacturing, etc.
- The economic progress achieved in the past six decades, along with a rapid expansion of global population, has come with a colossal environmental cost. While global GDP per capita has nearly tripled since 1960, CO_2 emissions have quadrupled during the same period.

CO_2 capture technologies as a potential solution

- Carbon Capture, Use, and Storage technologies (CCUS) have potential to capture more than 90% of carbon dioxide (CO_2) emissions from power plants and industrial facilities.
- Captured carbon dioxide can be put to productive use in enhanced oil recovery and the manufacture of fuels, building materials, and more, or be stored in underground geologic formations.
- Carbon capture can achieve 14% of the global greenhouse gas emissions reductions needed by 2050 and is viewed as the only practical way to achieve deep decarbonization in the industrial sector.
- A report from the United Nations' Intergovernmental Panel on Climate Change states that limiting global warming to 1.5 degrees Celsius (2.7 degrees Fahrenheit) over pre-industrial times will require not only swift, sharp cuts in carbon emissions from human sources, but **will also require still-unproven technology/process to remove heat-trapping carbon dioxide from the atmosphere including post-combustion capture, pre-combustion capture and oxyfuel carbon capture among other process.**

Figure 1 - Sources of anthropogenic CO_2 input by number of sources and by market sector.

One area of cost-effective CCS is the capture and purification of CO_2 from flue or fuel gas. In this area there is considerable room for cost reduction with the development of novel capture technologies.

Typical CO_2 emissions from various fuels used in combustion range from 2% to 20% CO_2 by volume (20,000 ppmv to 200,000 ppmv). Ideal characteristic of a CCS system addressing these emissions would have the following characteristics: flexibility to treat varying CO_2 concentrations, a low parasitic power demand, net positive cash flow generated by carbon credits and an end product of value, and of course, sequestration of the CO_2 to prevent re-release into the atmosphere. Combined, these characteristics would result in net negative carbon from the entire mass balance of the system including the carbon emitted by the produced products sequestering CO_2. Studies by the University of Madrid, Spain, studied 18 different CO_2 capture technologies including the most common ones promoted today: amine scrubbing and aqueous ammonia scrubbing. Of the 18 scenarios studied, only processes similar to the Montrose Carbon Conversion Process resulted in both net negative carbon and positive cash generation. Since this study, Montrose has improved on this process and further improved the negative carbon intensity and lowered the overall operating cost of our carbon conversion technology. Although the exact technology is not depicted in the graphic below, the scenarios most akin to the Montrose Carbon Conversion Process are #s 7, 10, 17, and 18.

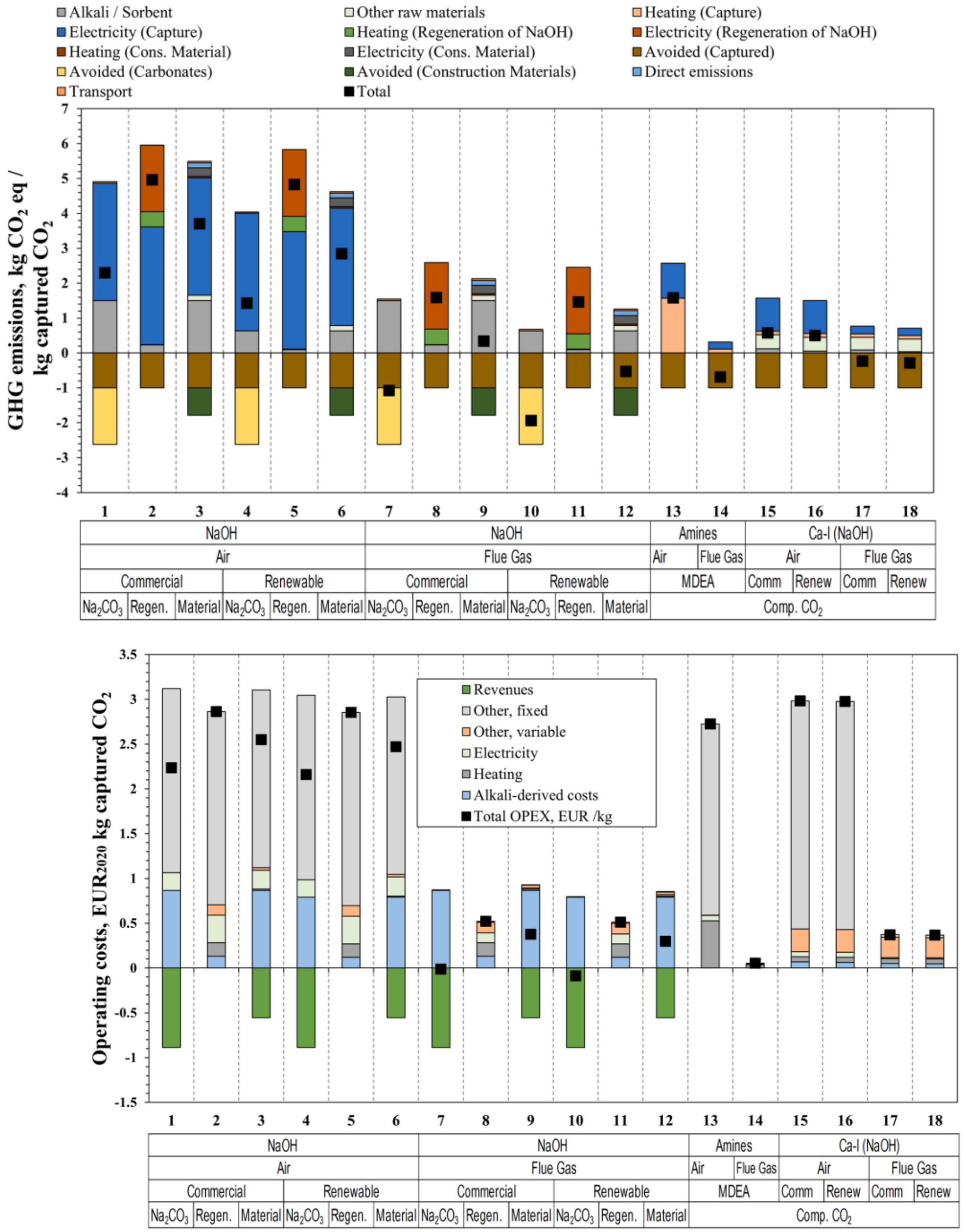


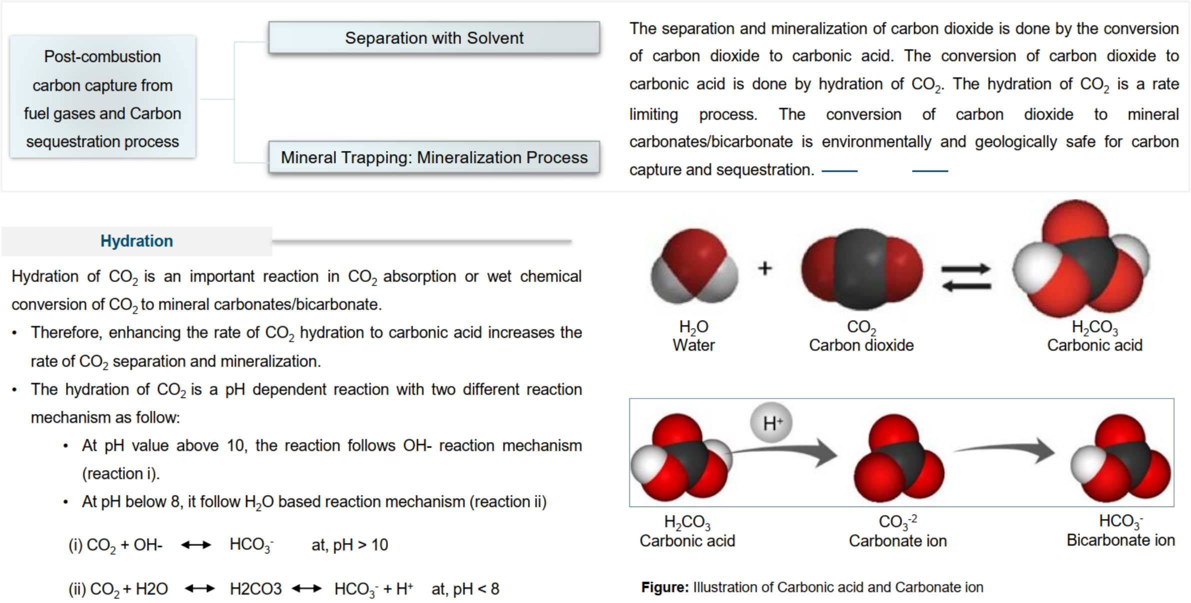
Figure 2 - Life Cycle Assessments of 18 different carbon capture scenarios showing a) top graphic, carbon intensity and b) bottom graphic, operating cost; the Montrose Carbon Conversion is not depicted but is most related to scenarios #7, 10, 17, and 18. Further optimization by Montrose has lowered both the Carbon Intensity and the Operating Costs. From Medina-Martos, et al, Environmental and economic performance of carbon capture with sodium hydroxide, Journal of CO2 Utilization, doi.org/10.1016/j.jcou.2022.101991; April 2022.

The Montrose Carbon Conversion technology is a proprietary system derived from the sodium hydroxide (NaOH) absorption process that performed so favorably in the Figure 2 above published by the University of Madrid. These technologies require an extremely low parasitic load, resulting in a net negative carbon intensity and positive return of funds to the owner. The system may be applied to sources with concentrations of up to 100% CO_2 with greater than

99.9% CO_2 removal. Generation of funds for the owner/operator of the system is capable through the production of a valuable carbonate product: either soda ash (Na_2CO_3) or sodium bicarbonate ($NaHCO_3$) . Uses for these materials are many. The manufacturing processes for glass, textiles, detergents, paper, and, most recently, lithium-ion batteries, all use soda ash. Acidic neutralization of wastewaters and preserving sensitive coral reef ecosystems involve the use of sodium bicarbonate. Other uses include mixing carbonates into soil as an amendment and incorporation into animal feed.

Application for carbonate products is widespread but today's conventional production of these products is not without environmental consequence. Referring only to soda ash, worldwide production is approximately 64 million metric tons per year. The Solvay process accounts for 75% of this, with the remainder being removed from trona mines. Both of these processes are very CO_2 intensive. One ton of CO_2 is generated for each ton of soda ash produced using the Solvay process. Less intensive, but still sizable, trona mining contributes between 0.3 – 0.7 tons CO_2 for every ton of soda ash produced. The Montrose Carbon Conversion Process turns this dynamic upside down. Able to produce sizeable carbonate volumes (~2 tons carbonate: 1-ton CO_2), the process is carbon negative; actually, removing carbon dioxide from a point source to create valuable products for use in many processes and non-industrial applications. In summary, the Montrose Carbon Conversion design may replace the Solvay process and capture enough carbon to obtain a net negative carbon score.

Previous studies by others using the solvents engaged in the Montrose Carbon Conversion design have failed to move forward into the mainstream because of kinetic limitations wetting the CO_2 molecule for quick interaction with various ionic liquids. The Montrose Carbon Conversion Process applies two internationally patent protected steps to quickly wet the CO_2 molecule forcing rapid interaction with an ionic fluid and instantaneous generation of carbonic acid. This results in the formation of carbonate salts that stay in solution until they reach solubility limits and are then filtered and processed into a high-purity, usable product. The graphic below provides additional details to this process.



The separation and mineralization of carbon dioxide is done by the conversion of carbon dioxide to carbonic acid. The conversion of carbon dioxide to carbonic acid is done by hydration of CO_2. The hydration of CO_2 is a rate limiting process. The conversion of carbon dioxide to mineral carbonates/bicarbonate is environmentally and geologically safe for carbon capture and sequestration.

Hydration

Hydration of CO_2 is an important reaction in CO_2 absorption or wet chemical conversion of CO_2 to mineral carbonates/bicarbonate.

- Therefore, enhancing the rate of CO_2 hydration to carbonic acid increases the rate of CO_2 separation and mineralization.
- The hydration of CO_2 is a pH dependent reaction with two different reaction mechanism as follow:
  - At pH value above 10, the reaction follows OH- reaction mechanism (reaction i).
  - At pH below 8, it follow H_2O based reaction mechanism (reaction ii)

(i) CO_2 + OH- ↔ HCO_3^- at, pH > 10

(ii) CO_2 + H2O ↔ H2CO3 ↔ HCO_3^- + H^+ at, pH < 8

Figure: Illustration of Carbonic acid and Carbonate ion

Figure 3 - Graphic showing hydration of gaseous CO2 molecule into aqueous carbonic acid molecule. Previous efforts by others have struggled with slow kinetics during this step. The Montrose Carbon Conversion Process has overcome this and transfers significantly more CO_2 transfer to solution and subsequent conversion into carbonate species.

Further optimization work by Montrose has led to an unprecedented gas-flow-to-solvent ratio of up to 20:1. This equates to an extremely low solvent use rate needed to remove 99.9+% CO_2 from a gas stream. Additionally, this process has an extremely low pressure drop when pushing gas through the system with resulting power requirements met with a single recirculation pump. A final added advantage is the complementary removal of acid gases and particulate, and even some heavy metals from combustion processes without compromising the removal efficiency of CO_2.

This approach is a simple, yet elegant and reliable, way to remove CO_2 from industrial processes, including from the production of ammonia, ethylene oxide, ethanol, cement, iron, and steel. Our process uses water as a non-toxic solvent to remove and permanently sequester CO_2 from waste exhaust streams. The Montrose Carbon Conversion Process has demonstrated continuous steady-state operation with nearly complete removal of CO_2 (99.9%+) – at a lower power consumption than amine-based or chilled ammonia technologies. The figure below demonstrates consistent CO_2 removal over time from a recent bench-scale effort. In the figure below, simple exposure to a solution of NaOH results in slow kinetics that are inefficient at converting the CO_2 in carbonic acid and finally to a carbonate salt. This can be seen when the proprietary process is turned off (at t = ~2000 minutes) and the CO_2 rapidly breaks through the ionic solvent solution when simply bubbling CO_2 through a venturi type injector to produce microbubbles.

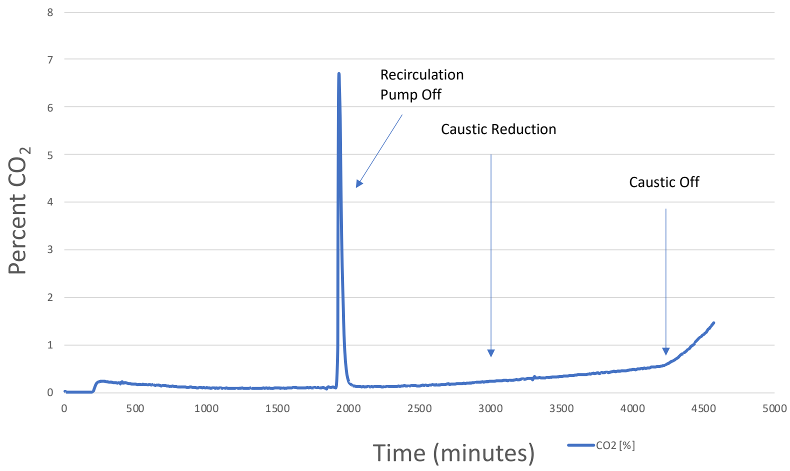


Figure 4 - Steady-state Operation of the Montrose Carbon Conversion technology. Influent CO_2 concentrations were 20% CO2 at a flow rate of 5 liters per minute in a bench top system.

Compared to other ionic fluids, the Montrose research and development team has studied many physio-chemical techniques and different ionic fluids and additives to improve gas transfer kinetics and the wettability of the CO_2 molecule in our capture system. This has resulted in our current design with unprecedented high gas flow rates and CO_2-to-solvent volumes that have not been achievable by today's standard scrubber designs. The figure below demonstrates some of the research results with different ionic fluids and additives.

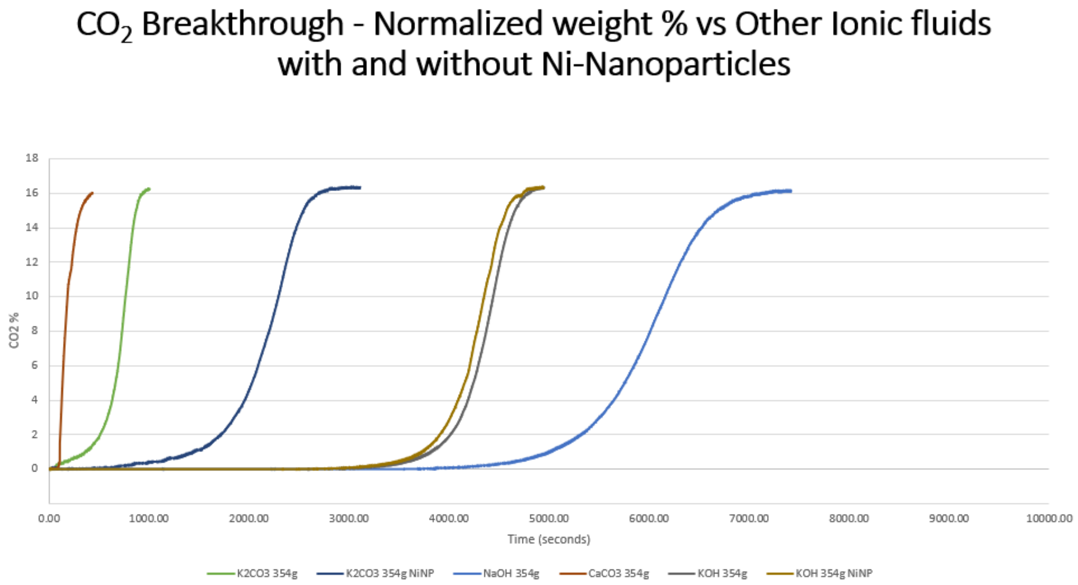
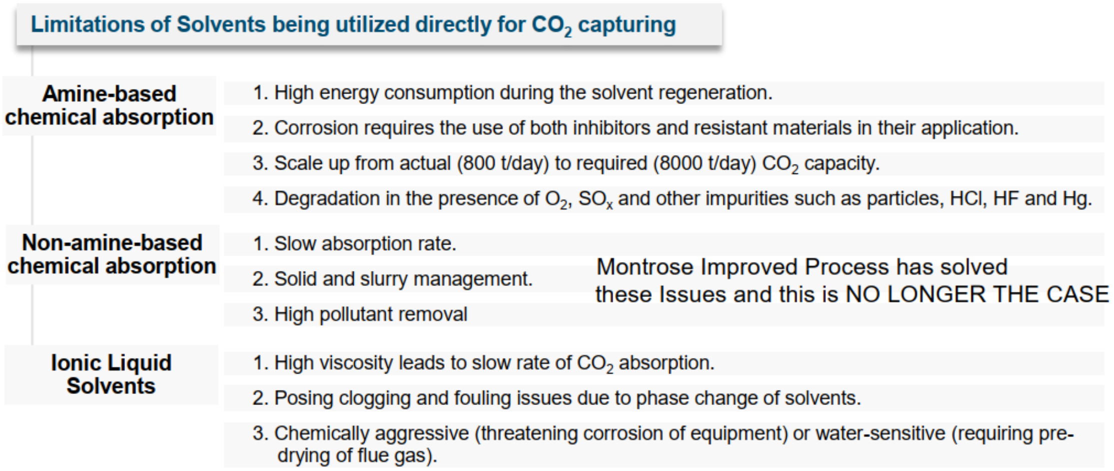


Figure 5 - CO2 breakthrough curves employing various solvents and additives. Influent CO2 concentrations were 20% CO_2 at a flow rate of 5 liters per minute in a bench top system containing less than 1 liter of solvent.

Previous work done to date has focused on using both amine-based and ionic liquid solvents. Carbon removal processes using these types of solvents have some negative attributes associated them which should be considered when selecting a technology. In addition to higher costs, adverse environmental characteristics and health risks have been linked with these solvents. Some of the limitations of solvents being utilized in CCS systems are listed in the graphic below.



Limitations of Solvents being utilized directly for CO_2 capturing

Amine-based chemical absorption	1. High energy consumption during the solvent regeneration.
	2. Corrosion requires the use of both inhibitors and resistant materials in their application.
	3. Scale up from actual (800 t/day) to required (8000 t/day) CO_2 capacity.
	4. Degradation in the presence of O_2, SO_x and other impurities such as particles, HCl, HF and Hg.
Non-amine-based chemical absorption	1. Slow absorption rate.
	2. Solid and slurry management.
	3. High pollutant removal
Ionic Liquid Solvents	1. High viscosity leads to slow rate of CO_2 absorption.
	2. Posing clogging and fouling issues due to phase change of solvents.
	3. Chemically aggressive (threatening corrosion of equipment) or water-sensitive (requiring pre-drying of flue gas).

Montrose Improved Process has solved these Issues and this is NO LONGER THE CASE

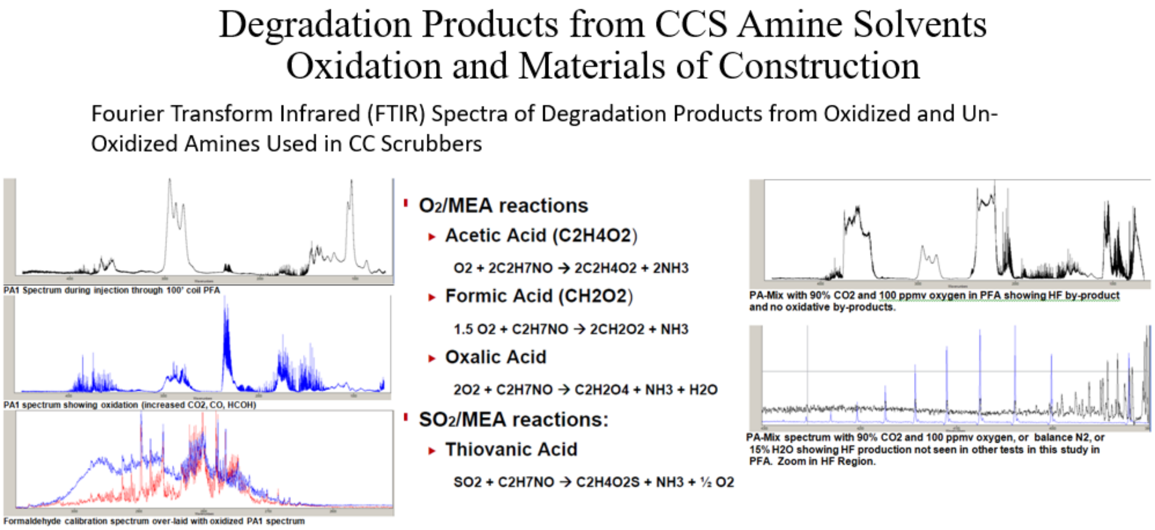
Figure 6 - Limitations of various solvents used in CCS technologies. The difficulties of the three different approaches have been overcome with the patented Montrose Carbon Conversion technology.

Compared to other capture designs, the Montrose Carbon Conversion system, using non-toxic solvents, avoids some of the drawbacks of convention solvent use. Some avoided characteristics of the water-based, non-toxic ionic solvents are shown in the table below.

Table 1 - Avoided characteristics of the water-based solvent used in the Montrose Carbon Conversion technology.

Montrose Carbon Capture Process – Solvent Characteristics	
No Harmful Degradation Products	✖
No Odor-control Issues	✖
No Flue Gas Desulfurization Step (avoids processing complications and high parasitic load)	✖
No Risk of Contamination to Groundwater with Accidental Environmental Release	✖

With amine-based approaches, solvent loses can be significant. Constant solvent replenishment increases cost and operational oversight and complexity to operations. Additionally, our research has identified hazardous air emissions as degradation products from amine-based processes. Figure 7 below details some of these findings. Depending upon emission levels and permitting conditions, these emissions may require additional control technologies adding cost and complexity to projects.



Degradation Products from CCS Amine Solvents
Oxidation and Materials of Construction

Fourier Transform Infrared (FTIR) Spectra of Degradation Products from Oxidized and Un-Oxidized Amines Used in CC Scrubbers

PA1 Spectrum during injection through 100' coil PFA

PA1 spectrum showing oxidation (increased CO2, CO, HCOH)

Formaldehyde calibration spectrum over-laid with oxidized PA1 spectrum

- **O_2/MEA reactions**
  - **Acetic Acid (C2H4O2)**
    $\mathrm{O2 + 2C2H7NO \rightarrow 2C2H4O2 + 2NH3}$
  - **Formic Acid (CH2O2)**
    $\mathrm{1.5\ O2 + C2H7NO \rightarrow 2CH2O2 + NH3}$
  - **Oxalic Acid**
    $\mathrm{2O2 + C2H7NO \rightarrow C2H2O4 + NH3 + H2O}$
- **SO_2/MEA reactions:**
  - **Thiovanic Acid**
    $\mathrm{SO2 + C2H7NO \rightarrow C2H4O2S + NH3 + ½\ O2}$

PA-Mix with 90% CO2 and 100 ppmv oxygen in PFA showing HF by-product and no oxidative by-products.

PA-Mix spectrum with 90% CO2 and 100 ppmv oxygen, or balance N2, or 15% H2O showing HF production not seen in other tests in this study in PFA. Zoom in HF Region.

Figure 7 - Internal investigation identifying hazardous air emissions from amine-bases technologies. Based upon site specific locations, these emissions may justify installation of control technologies adding time, cost, and complexity to projects.

In summary, the Montrose CO_2 conversion process uses a 2-stage, patent-protected approach with low-energy consumption, but a rapid and efficient gas-transfer step that overcomes kinetic and mass-transfer problems encountered in previous carbon capture technology attempts using ionic fluids. The process allows the removal of CO_2 from a variety of influent sources containing CO_2 concentrations ranging from ambient to 100%. A block flow diagram of the process is shown in Figure 8.

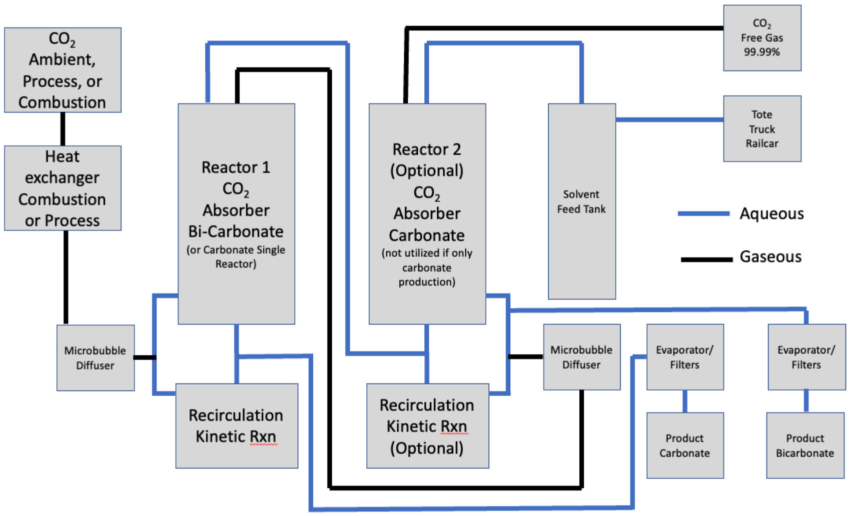


Figure 8 - Simplified block flow diagram showing the Montrose Carbon Conversion Process.

This process was tested in our research and development laboratories and can be easily scaled up with a comparably smaller footprint than scrubber technologies, such as amine liquids. A notional image of a pilot skid is provided in Figure 9. The footprint of a pilot unit is small at approximately 10’ x 10’. We anticipate a run-time of approximately 4 weeks would allow the process to be optimized to the unique process treated and generate collection of enough data to demonstrate proof of concept and allow accurate scale-up calculations to be completed.

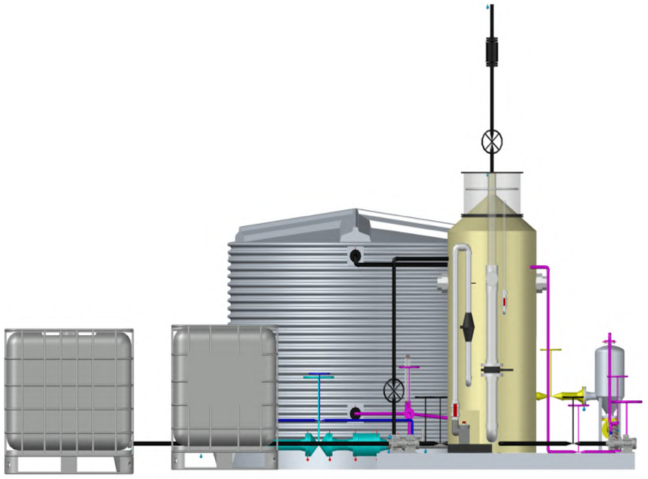


Figure 9 - Notional layout of Montrose Carbon Conversion technology deployed in a pilot configuration. The expected footprint of a pilot is approximately 10’ x 10’ and involves 2 IBC totes, a 1000-gallon polyethylene cooling tank (to be substituted out in a in a full-scale unit), a 500 gallon carbon conversion reactor and associated programable logic.

As an ancillary benefit, other contaminants, such as hydrogen sulfide, other acid gases, carbon monoxide, some heavy metals, and other emission contaminants in the flue gas, will be removed via this process allowing a facility to combine other emissions control devices with our patented Montrose Carbon Conversion Process. This may eliminate capital cost (CAPEX) and operational cost (OPEX) from separate control devices.

Based on operating conditions, the characteristics of the waste gas stream being treated, and preferences of the customer, the CO_2 is directly sequestered into different carbonate species that are ideal for beneficial use in other industrial applications. Ideally, the carbonate species can be used in customer operations on-site. Otherwise, the product is applicable for use in several manufacturing processes, as a soil amendment, or as an additive to animal feed. Other uses could include amendments to de-acidify coral reefs or for wastewater and digester neutralization.

When considering the reuse of waste heat, the low parasitic load of the process, and the reusable carbonate product, the Montrose Carbon Conversion Process results in an overall negative carbon intensity score. If renewable energy sources are used to power the process, even lower carbon intensity scores can be achieved. Assuming minimum annual thresholds of carbon oxides are obtained (recently reduced with the 2022 Inflation Reduction Act to 18,750 metric tons per year for power plants and 12,500 metric tons per year for industrial facilities) the Montrose Carbon Conversion Process will qualify for 45Q tax credits and direct pay subsidies.

If you are interested in learning more about the Montrose Carbon Conversion Process and how a small footprint, low-cost pilot system can be set up on your site to meet your CO_2 reduction goals, please call us at +1-919-522-2032 or pzemek@montrose-env.com to discuss further details and partnerships.