Managing global carbon emissions is one of the most pressing environmental concerns of our time. Many scientists are concerned that anthropogenic (human-made) greenhouse gases (GHGs) are affecting Earth’s climate. Although earth-warming gases exist naturally in the atmosphere, human activities are adding more of these GHGs, including carbon dioxide ($\text{CO}_2$). The challenge is to address anthropogenic GHG emissions while providing access to reliable, affordable, resilient energy around the world. Carbon capture, utilization, and storage (CCUS) can address this challenge, and the activities conducted through the Plains $\text{CO}_2$ Reduction (PCOR) Partnership are playing an important role in developing and deploying CCUS technologies.
At the heart of this challenge is Earth’s natural greenhouse effect, which plays an essential role in our climate patterns. The effect is the result of heat-trapping gases (called GHGs), which absorb heat emitted from Earth’s surface and lower atmosphere and then release much of the heat back toward the surface. Without this greenhouse effect, the average surface temperature of Earth would be about 0°F (or −18°C) instead of 59°F (15°C), and life as it is known would not be possible.

1. Sun’s rays enter Earth’s atmosphere.
2. Heat is emitted back from Earth’s surface.
3. Some heat passes back out into space.
4. Some heat is absorbed by GHGs and becomes trapped within Earth’s atmosphere. Earth becomes hotter as a result. The more GHGs in the atmosphere, the more heat is retained.
Many gaseous chemical compounds in Earth’s atmosphere contribute to the greenhouse effect. These gases absorb infrared radiation emitted from Earth’s surface and trap the heat in the atmosphere. Some of these gases occur in nature, while others are products of human activity.

WATER VAPOR ($\text{H}_2\text{O}$) is the most abundant GHG in the atmosphere. As the temperature of the atmosphere rises, it can hold more water vapor. This higher concentration of water vapor is able to absorb more heat, further warming the atmosphere. This cycle is called a feedback loop. Water molecules have very little heat-trapping capacity compared to other GHGs, and thus changes to the amount of water vapor have the least impact on the greenhouse effect.

CARBON DIOXIDE has both natural and anthropogenic (human-made) sources. $\text{CO}_2$ plays a vital role in supporting life on Earth through the global carbon cycle. The heat-trapping capacity of $\text{CO}_2$ molecules is much greater than water vapor. Because its production is so prevalent in human activity, $\text{CO}_2$ is the major focus of GHG reduction efforts.

METHANE ($\text{CH}_4$) has both natural and anthropogenic sources. Human activities such as growing crops, raising livestock, using natural gas, and mining coal have added to the atmospheric concentration of methane. Although the heat-trapping capacity of methane molecules is 28–36 times that of $\text{CO}_2$, the amount of methane produced by human activities is much less.

NITROUS OXIDE ($\text{N}_2\text{O}$) has both natural and anthropogenic sources associated with agricultural, land use, and industrial activities. A product of decomposition, $\text{N}_2\text{O}$ is produced by microbial processes in soil and water, including those reactions that occur in fertilizer containing nitrogen, in both solid waste and wastewater treatment, and during combustion (because nitrogen is the major component of air).

OZONE ($\text{O}_3$) is formed in the stratosphere through the interaction between ultraviolet light and oxygen. This natural $\text{O}_3$ layer has been supplemented by $\text{O}_3$ created by human processes, such as automobile exhaust and burning vegetation.

Human contributions of GHGs to the atmosphere may seem minor compared to the large share of water vapor and clouds. The heat-trapping capacity of these molecules is, however, much greater than water vapor, so smaller changes have a greater impact.
As part of the natural carbon cycle, people and animals inhale oxygen from the air and exhale CO₂. Meanwhile, green plants absorb CO₂ for photosynthesis and emit oxygen back into the atmosphere. Marine biota, sediments, and the ocean water itself also absorb CO₂ and/or carbon-rich matter. Decomposition also returns CO₂ to the atmosphere. This exchange, or flux, of carbon among the atmosphere, oceans, and land surface is called the global carbon cycle.¹

For most of human history, the global carbon cycle has been roughly in balance. The amount of carbon in the atmosphere is approximately 860 billion tonnes (or gigatonnes, Gt), which is more carbon than contained in all of Earth’s living vegetation and roughly 80 Gt more than in 2000. Human activities, namely, the burning of fossil fuels, deforestation, farming, and other land use activities, have altered the carbon cycle, adding extra CO₂ to the atmosphere. Earth’s ocean and terrestrial environments compensate for some of the excess by taking up billions of tonnes of extra CO₂ (shown in red in the figure). Still, much remains in the atmosphere, resulting in a 45% increase in atmospheric concentrations of CO₂ since the Industrial Revolution.

Averaged annual emissions, 2010–2019. Fluxes and pools are in GtC. Pools are noted in parentheses.
More than 100 years ago, Swedish scientist and Nobel Prize winner Svante Arrhenius postulated that anthropogenic increases in atmospheric CO₂ as the result of fossil fuel combustion would have a profound effect on the heat budget of Earth. In 1904, Arrhenius became concerned with rapid increases in anthropogenic carbon emissions.

Since instrumental records of temperature began in 1880, the overall temperature of Earth has risen by more than 2°F (1.2°C), with 2020 being the second warmest year on record according to the National Oceanic and Atmospheric Administration. The world’s seven warmest years have all occurred since 2014. These rising temperatures are causing wide-ranging impacts such as the loss of sea ice and ice sheet mass, sea level rise, longer and more intense heat waves, and shifts in habitats. Most climate scientists attribute these current changes in climate at least in part to anthropogenic (human-made) GHG emissions.

The map shows the average surface temperature trends for the decade 2005–2015 relative to the 1950–1980 average. Warming was more pronounced at high latitudes, especially in the Northern Hemisphere and over land.

CLIMATE CHANGE PATTERNS
MAJOR STATIONARY CO$_2$ SOURCES

INDUSTRIAL

Cement Plant

PETROLEUM AND NATURAL GAS

Refinery

ELECTRIC UTILITY

Coal-Fired Power Plant

AGRICULTURE-RELATED PROCESSING

Ethanol Plant
Carbon dioxide produced through human action is referred to as anthropogenic CO$_2$. The primary source of anthropogenic CO$_2$ emissions in North America is the burning of fossil fuels for energy. Industrial activities such as manufacturing cement, producing ethanol, refining petroleum, producing metals, and combusting waste also contribute a significant amount of anthropogenic CO$_2$. Collectively, these are referred to as large stationary CO$_2$ point sources. Nonstationary CO$_2$ emissions include activities such as using gasoline, diesel, and other fuels for transportation.

Changes in land use and land conversion also contribute to anthropogenic CO$_2$ emissions. This includes practices like plowing land, which releases exposed carbon in the soil to the atmosphere as CO$_2$, and deforestation, which reduces plant biomass, thus reducing the plant uptake of airborne CO$_2$ and releases CO$_2$ if the biomass is burned.

**WHAT IS CO$_2$?** Carbon dioxide is a colorless, odorless, naturally occurring gas comprising one atom of carbon and two atoms of oxygen. At temperatures below −76°C, CO$_2$ condenses into a white solid called dry ice. When warmed, dry ice vaporizes directly from a solid to a CO$_2$ gas in a process called sublimation. With enough added pressure, liquid CO$_2$ can be formed. CO$_2$ has many industrial uses: in fire extinguishers, as a propellant in spray cans, in treatment of drinking water, for cold storage (CO$_2$ as dry ice), and to make bubbles in soft drinks. CO$_2$ is also used in large quantities for enhanced oil recovery (EOR) as part of oil production in some oil fields.

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**2018 GLOBAL GREENHOUSE GAS EMISSIONS**

- Energy-Related CO$_2$: 32%
- Non-Energy-Related CO$_2$: 72%
- Fluorinated GHGs: 5%
- Nitrous Oxide: 6%
- Methane: 17%
- Buildings: 13%
- Manufacturing and Construction: 17%
- Transport: 6%
- Electricity and Heat: 2%

About 2.4% of CO$_2$ emissions in 2018 results from agricultural, land use, and forestry practices. Other GHG emissions occurred in agriculture, fugitive emissions, manufacturing and construction, waste, industry, other fuel combustion, land use changes, and forestry.

*Percentages exceed 72% because of rounding. The other category includes 3.1% industry, 1.3% other fuel combustion, and 0.5% fugitive emissions.*
The amount of CO$_2$ in the atmosphere was relatively constant for 10,000 years until the Industrial Revolution in the 1800s, when the amount of anthropogenic CO$_2$ increased considerably. Currently, the world’s economies annually emit approximately 35 Gt of CO$_2$ to the atmosphere from the combustion of fossil fuels to produce electricity. Increasing global populations, higher standards of living, and increased demand for energy will likely result in continued increases in global CO$_2$ emissions.
1911 Carrier invents air conditioner.
1920 9 million autos in the United States.
1936 Rural electrification of the United States begins.
1939 First tanker of oil ships from Middle East.
1949 U.S. coal production tops 1 billion tons/yr.
1973 Arab oil embargo.
2007 54.9 million cars produced.
2020 Impact of the COVID-19 pandemic drastically alters global energy demand which lowers CO₂ emissions.
Since 1970, global CO₂ emissions have increased nearly 150%, with emissions from fossil fuel combustion and industrial processes contributing nearly 75% of the total emissions in 2018. To reduce the growing impact of CO₂ emissions on climate change, policies and regulations have been developed on a national and global level.

Ten economies account for about 73% of global CO₂ from energy and industrial processes. Illustrated in the comparison, the 4.6-billion-metric-ton increase in emissions from 2008 to 2018 comes mainly from five of these countries, including major increases in emissions in China, India and, to a lesser extent, Indonesia as they work to modernize their economies and provide more economic opportunities for their inhabitants.

Four of the top ten emitting economies had lower CO₂ emissions in 2018 as compared to 2008. The savings from these four economies offset the 14% increase in CO₂ emissions from the rest of the world. The greatest percentages of decrease are 15% and 10% for the European Union (EU, 27 nations) and the United States, respectively.
All member countries of the United Nations Framework Convention on Climate Change (UNFCCC) agreed to adopt a new global climate agreement, named the Paris Agreement, in December 2015. This agreement aims to limit the rise in global average surface temperature to well below 2°C, and preferably below 1.5°C, compared to preindustrial levels to avoid the most dangerous impacts of climate change. The Paris Agreement requires 5-year cycles of increasing climate action to be carried out by the participating countries. As of June 2021, 192 parties have submitted their first nationally determined contributions (NDCs). The NDCs are the climate actions that each country will take to contribute to reaching the goals of the Paris Agreement. Eight parties have submitted their second.14

CO₂ emissions have strong ties to economic activity. Even economies with lower CO₂ emissions in 2018 may be net importers of CO₂ emissions from trade,12 highlighting the need for a global focus on strategies to reduce emissions.
AGRICULTURE-RELATED PROCESSING
In addition to being the world's largest producer and exporter of corn, the corn belt region of the United States represents the most intensive agricultural region of the Midwest. Although most of the corn is used for livestock feed, a significant portion is sent to ethanol plants in the region. Ethanol plants are a source of nearly pure CO₂ and thus require no specialized CO₂ capture and separation technologies.

PETROLEUM AND NATURAL GAS
The large concentration of sources along the eastern edge of the Rocky Mountains associated with petroleum and natural gas production is a reflection of the amount of energy needed to extract and refine hydrocarbon resources needed for transportation, heating, and industry.

ELECTRICAL UTILITY
In 1882, the world's first central generating plant was installed on Pearl Street in New York's financial district. Since then, the use of electricity has grown from street lamps and in homes to supplying vast energy grids that supply power to entire cities. Although a large concentration of these sources is on the East Coast of the United States, due mostly to population, these sources are well distributed throughout North America.

INDUSTRIAL MANUFACTURING
The Great Lakes region in the United States is a robust center of industrial manufacturing. Food processing, iron and steel production, and textile and automotive manufacturing are some of the many activities that consume large quantities of energy and produce significant amounts of CO₂.
Addressing climate change is a large-scale, global challenge that is compounded by our growing demand for energy. To reduce the risks associated with climate change, the amount of CO₂ released by human activity must be substantially reduced.

A number of techniques can be employed to reduce CO₂ emissions, including energy conservation, using fossil fuels more efficiently, and increasing the use of renewable (i.e., wind, solar, geothermal, hydropower) and nuclear energy. But in the face of growing world populations and rising worldwide standards of living, CCUS provides an opportunity to combine the continued use of fossil fuels with a significant reduction in GHG emissions. CCUS lies at the intersection of energy, the economy, and the environment, which makes it a critical approach to meet our world’s clean energy needs. The PCOR Partnership is working to ensure that CCUS is developed and implemented in a practical and environmentally sound manner.

CCUS captures around 40 million metric tons of CO₂ per year worldwide, with 17 new CCUS projects coming online in 2020.¹⁷

Global Status of CCS Report 2020
Over the past 15 years, increasing concerns over the potential impacts of climate change and increasing competition from natural gas and renewable energy sources have caused a significant shift in the U.S. energy production profile. Today coal generates about 20% of the U.S. net power generation—down from 50% in 2005. Although much of that decrease has been offset by natural gas power generation, an increasingly larger portion of power generation is coming from low-carbon renewables, such as wind and solar.

Increasing reliance on low-carbon renewable energy sources may sacrifice grid resilience and reliability. These concerns have been amplified during recent extreme weather events in the United States when much of the country was without power. A significant challenge in reducing the reliance on fossil fuels in the energy sector is to find solutions to the shortcomings of renewable energy in an economically feasible manner.

Traditional power plants equipped with CCUS technology can play an important role to ensure that low-carbon power generation of the future can evolve without sacrificing resilience and reliability. A recent study by the International Energy Agency (IEA) concludes that when accounting for system reliability and flexibility, the competitiveness of carbon capture in the power system increases relative to other generation sources. Thus CCUS-enabled power production can contribute to energy security while complementing and facilitating the increased deployment of renewables.

Although the total amount of electricity generated for the U.S. grid has remained relatively constant over the last 15 years, the primary energy used to generate electricity has changed dramatically. Factors in the change include the price of natural gas, tax incentives for renewables, and pressure to reduce CO₂ emissions from energy production.