CHAPTER 1

THE CHALLENGE

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 (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 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)[1] instead of 59°F (15°C) and life as it is known would not be possible.

Many gaseous chemical compounds in Earth's atmosphere contribute to the greenhouse effect.[2] 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 (H_2O) 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.

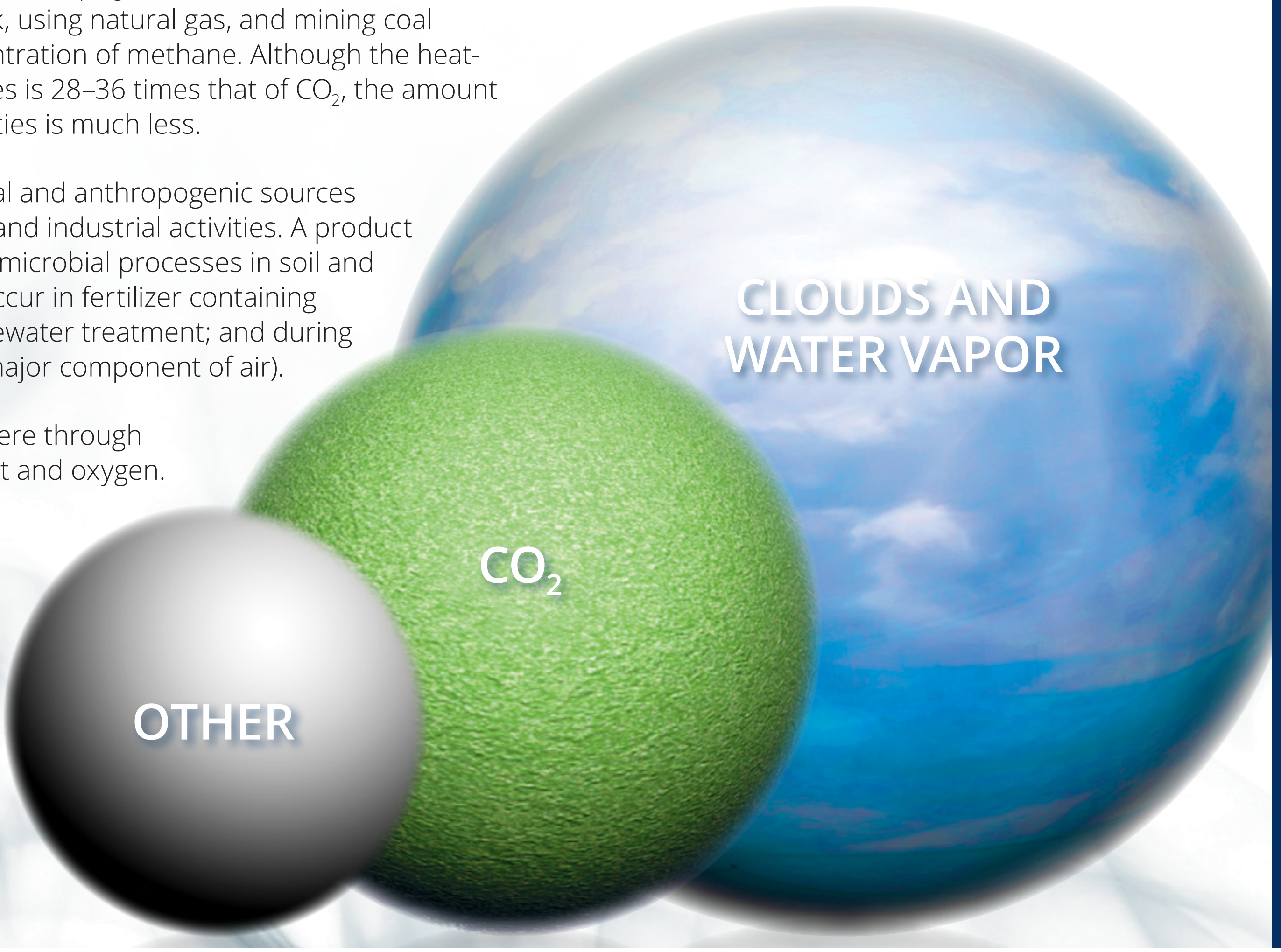
CARBON DIOXIDE has both natural and anthropogenic sources. CO_2 plays a vital role in supporting life on Earth through the global carbon cycle. The heat-trapping capacity of CO_2 molecules is much greater than water vapor. Because its production is so prevalent in human activity, CO_2 is the major focus of GHG reduction efforts.

METHANE (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 CO_2, the amount of methane produced by human activities is much less.

NITROUS OXIDE (N_2O) has both natural and anthropogenic sources associated with agricultural, land-use, and industrial activities. A product of decomposition, N_2O 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 (O_3) is formed in the stratosphere through the interaction between ultraviolet light and oxygen. This natural O_3 layer has been supplemented by O_3 created by human processes, such as automobile exhaust and burning vegetation.

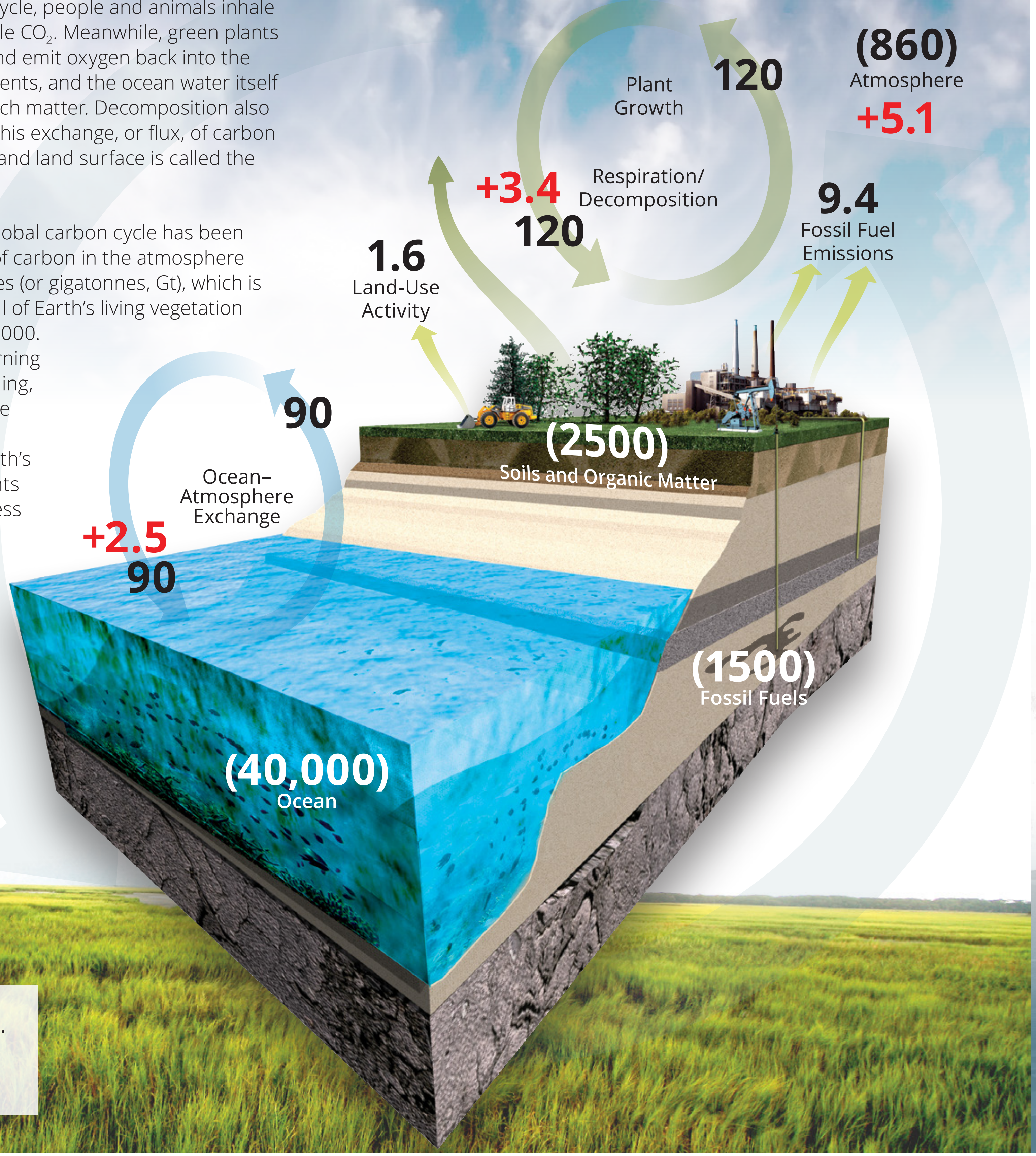
Human contributions of GHGs to the atmosphere may seem minor compared to the large share of water vapor and clouds. The heat-trapping capacity of these molecules is, however, much greater than water vapor, so smaller changes have a greater impact.



Relative total GHG effect contributions.[3]

As part of the natural carbon cycle, people and animals inhale oxygen from the air and exhale CO_2. Meanwhile, green plants absorb CO_2 for photosynthesis and emit oxygen back into the atmosphere. Marine biota, sediments, and the ocean water itself also absorb CO_2 and/or carbon-rich matter. Decomposition also returns CO_2 to the atmosphere. This exchange, or flux, of carbon among the atmosphere, oceans, and land surface is called the global carbon cycle.[4]

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 CO_2 to the atmosphere. Earth's ocean and terrestrial environments compensate for some of the excess by taking up billions of tonnes of extra CO_2 (shown in red in the figure). Still, much remains in the atmosphere, resulting in a 45% increase in atmospheric concentrations of CO_2 since the Industrial Revolution.

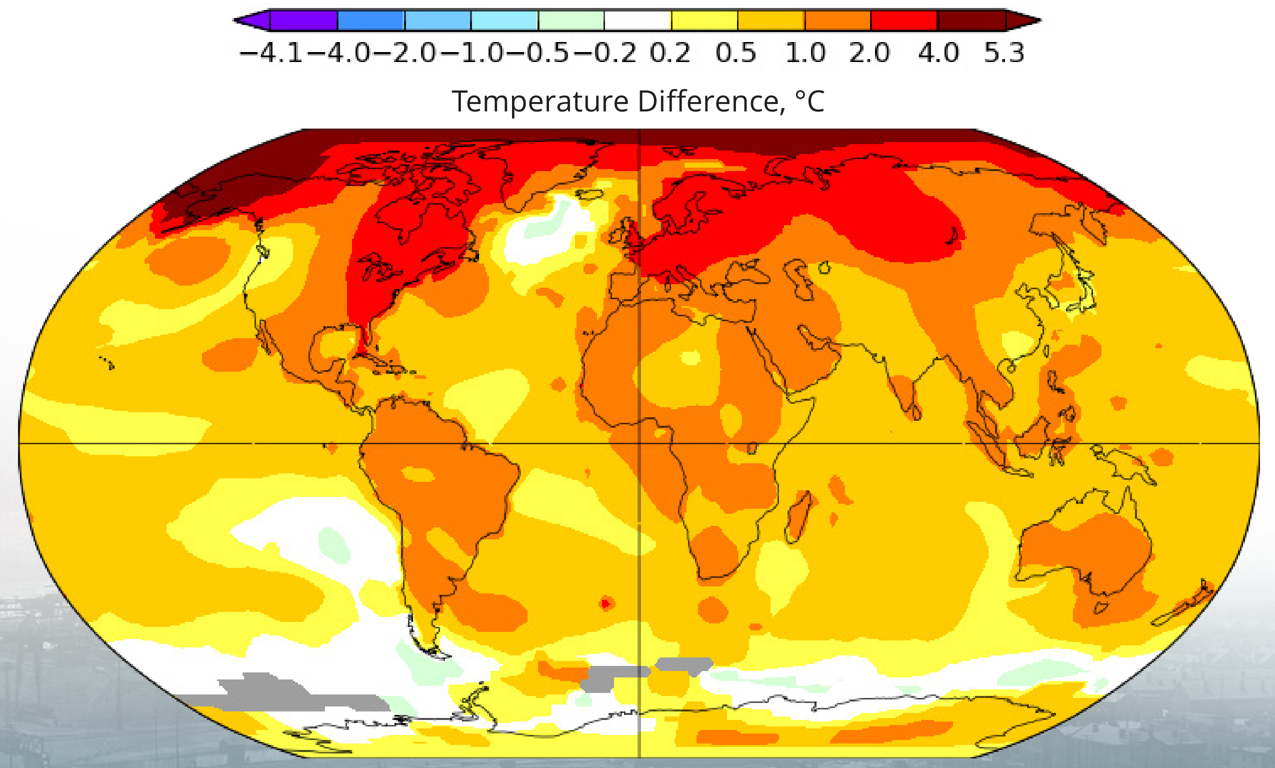


Averaged annual emissions, 2010–2019.
Fluxes and pools are in Gt of carbon.
Pools are noted in parentheses.

> "The slight percentage of carbonic acid in the atmosphere may, by the advances of industry, be changed to a noticeable degree in the course of a few centuries."
>
> Svante Arrhenius, 1904

Since instrumental records of temperature began in 1880, the overall temperature of Earth has risen by more than 2°F (1.2°C), with 2023 being the warmest year on record according to the National Oceanic and Atmospheric Administration.[5] The world's 10 warmest years have all occurred in the last 10 years. 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 GHG emissions.

The map shows the average surface temperature trends for 2013–2023 relative to the 1991–2020 average. Warming was more pronounced at high latitudes, especially in the Northern Hemisphere and over land.[6]



More than 100 years ago, Swedish scientist and Nobel Prize winner Svante Arrhenius postulated that anthropogenic increases in atmospheric CO_2 as the result of fossil fuel combustion would profoundly affect the heat budget of Earth. In 1904, Arrhenius became concerned with rapid increases in anthropogenic carbon emissions.[7]

MAJOR STATIONARY CO_2 SOURCES

INDUSTRIAL

Cement Plant

PETROLEUM AND NATURAL GAS

Refinery

ELECTRIC UTILITY

Coal-Fired Power Plant

AGRICULTURE-RELATED PROCESSING

Ethanol Plant

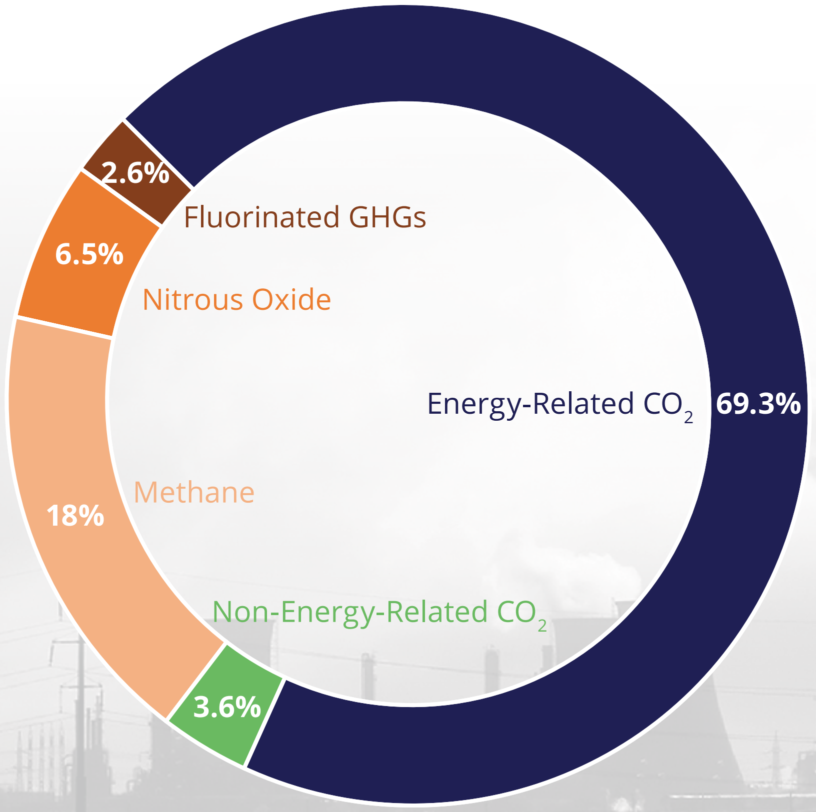
ANTHROPOGENIC CO_2

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.

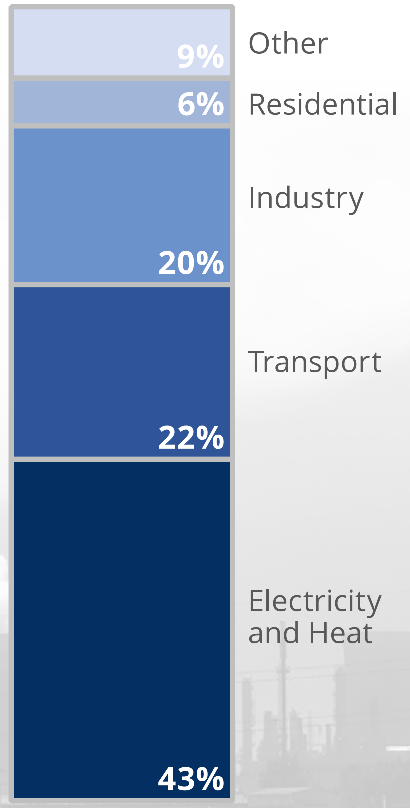
Changes in land use and land conversion also contribute to anthropogenic CO_2 emissions. These include practices like plowing land, which releases exposed carbon in the soil to the atmosphere as CO_2, and deforestation, which reduces plant biomass, thus reducing the plant uptake of airborne CO_2. Deforestation also 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.

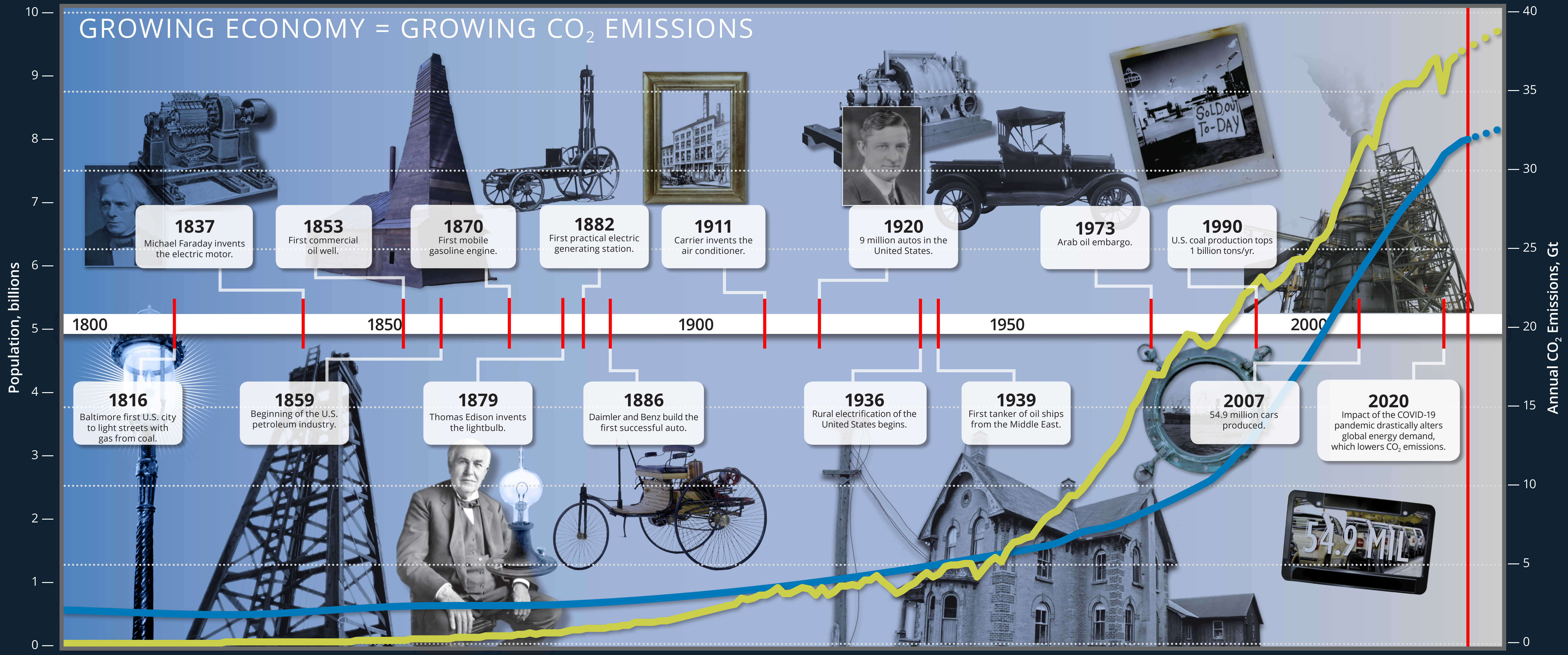
2020 GLOBAL GHG EMISSIONS[8]



2020 GLOBAL CO_2 FROM FUEL COMBUSTION BY SECTOR[9]

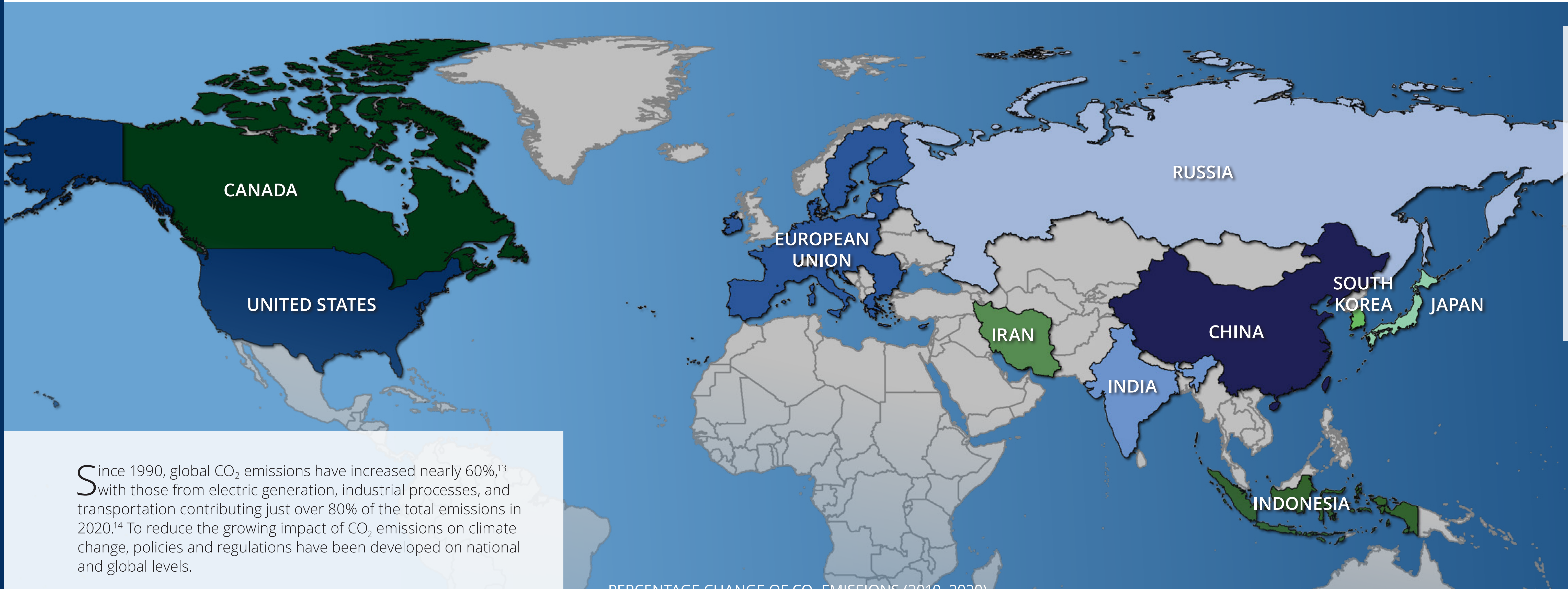


GROWING ECONOMY = GROWING CO_2 EMISSIONS



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, humans' combustion of fossil fuels to produce electricity emits approximately 37 Gt of CO_2 to the atmosphere annually. Increasing global populations, higher standards of living, and increased demand for energy will likely result in continued increases in global CO_2 emissions.

WORLD CO_2 EMISSIONS



The United Nations Framework Convention on Climate Change held its 28th meeting of the Conference of the Parties climate change conference (COP 28) in Dubai, United Arab Emirates, from November 30 to December 13, 2023. COP 28 was the first global stocktake by nearly 200 parties since the Paris Agreement in 2015. Because of slow progress across all areas of climate action, countries outlined plans to accelerate action by 2030. These plans include a call for governments to speed up the transition away from fossil fuels in their next round of climate commitments.

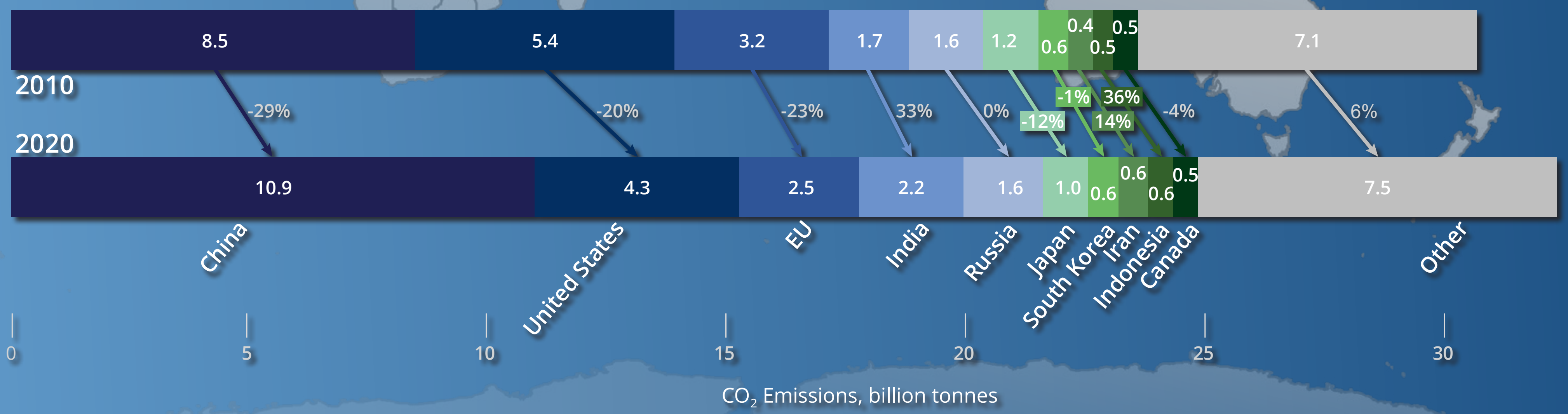
The global stocktake was considered the central outcome of COP 28 and can be used by countries to develop stronger climate action plans that are due by February 2025. The stocktake aims to cut GHG emissions by 43% by 2030 compared to 2019 levels to limit global temperature increase to 1.5°C.[15]

Since 1990, global CO_2 emissions have increased nearly 60%,[13] with those from electric generation, industrial processes, and transportation contributing just over 80% of the total emissions in 2020.[14] To reduce the growing impact of CO_2 emissions on climate change, policies and regulations have been developed on national and global levels.

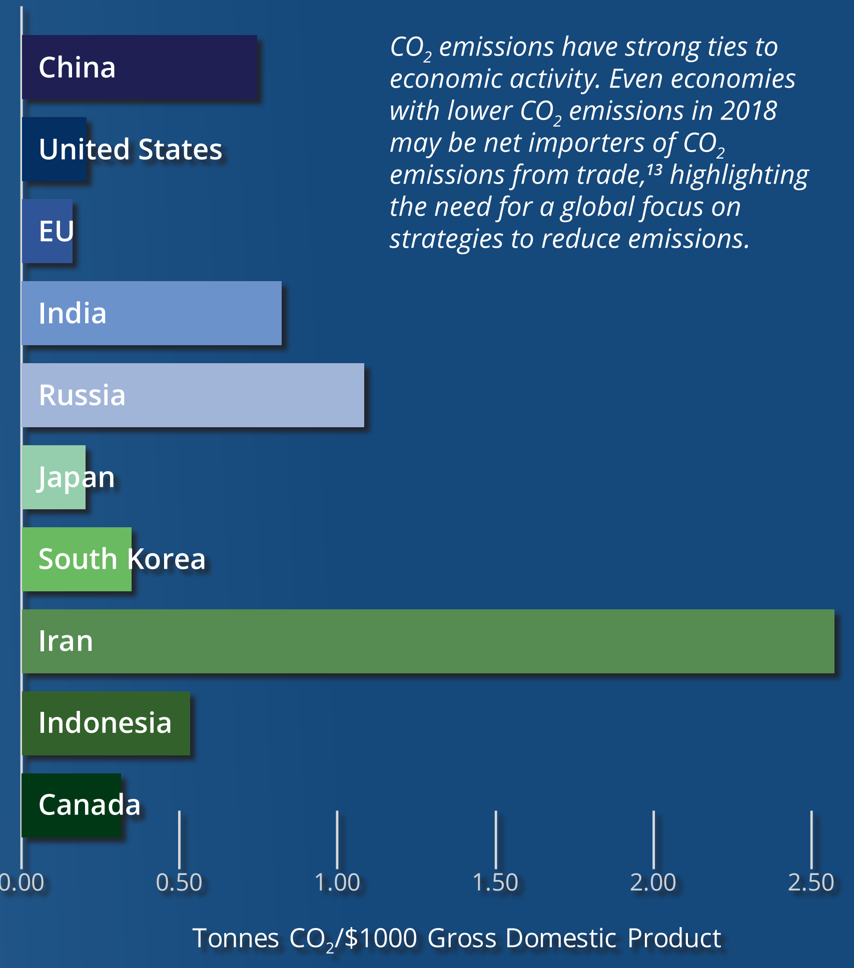
Ten economies account for about 78% of global CO_2 from energy and industrial processes. Illustrated in the bar graph, right, the 1.7-Gt increase in emissions from 2010 to 2020[14] comes mainly from five of these countries, including major increases in emissions in China, India and, to a lesser extent, Indonesia as they work to modernize their economies and provide more economic opportunities for their inhabitants.

Five of the top ten emitting economies had lower CO_2 emissions in 2020 as compared to 2010. The savings from these five economies offset the 5% increase in CO_2 emissions from the rest of the world. The greatest percentages of decrease are 23% and 20% for the European Union (EU, 27 nations) and the United States, respectively.

PERCENTAGE CHANGE OF CO_2 EMISSIONS (2010–2020)

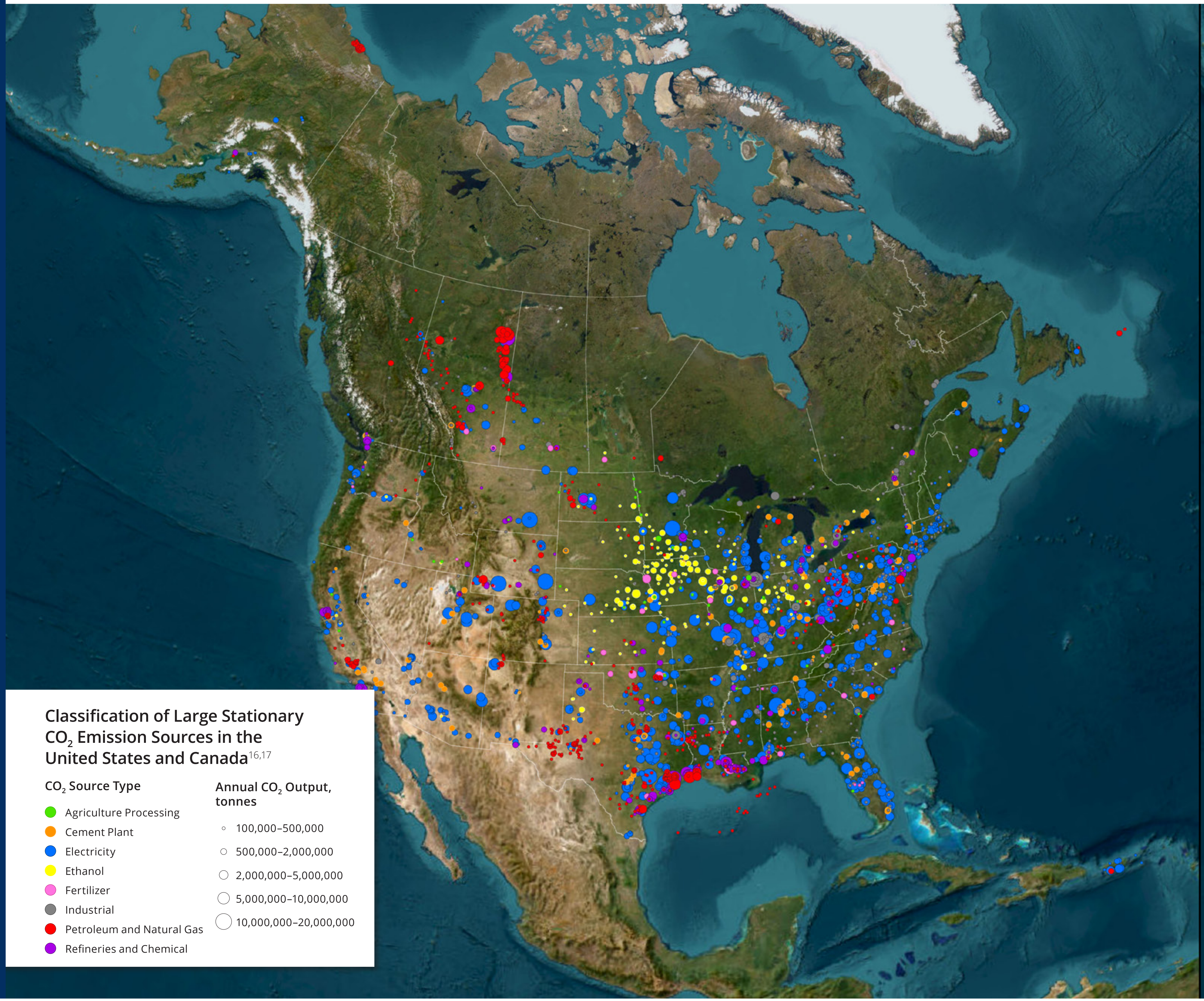


RATIO OF CO_2 EMISSIONS TO GROSS DOMESTIC PRODUCT FOR WORLD ECONOMIES (2018)

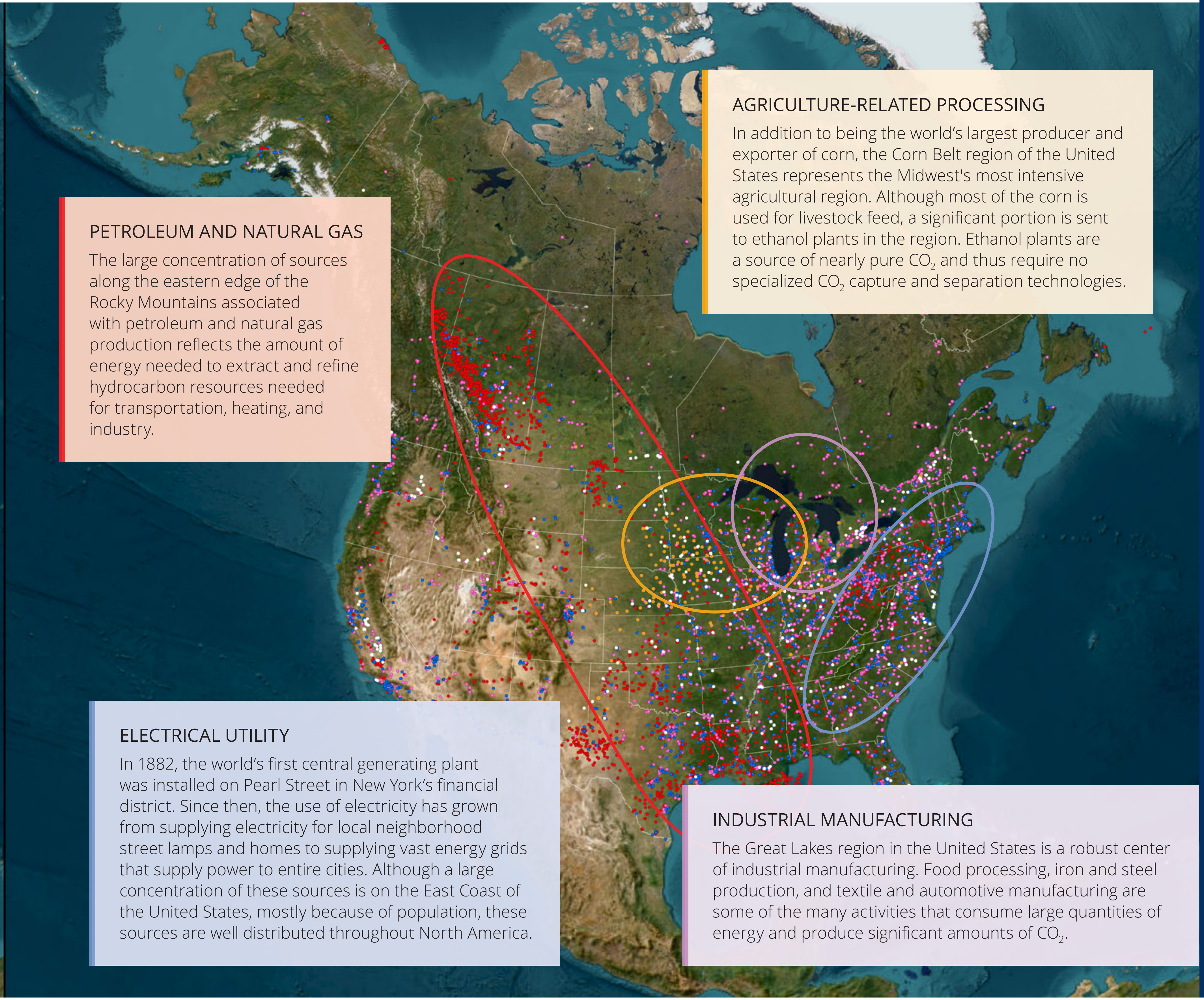


CO_2 emissions have strong ties to economic activity. Even economies with lower CO_2 emissions in 2018 may be net importers of CO_2 emissions from trade,[13] highlighting the need for a global focus on strategies to reduce emissions.

U.S. AND CANADIAN CO_2 SOURCES



U.S. AND CANADIAN PROFILE



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 Midwest's most intensive agricultural region. 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 CO_2 and thus require no specialized CO_2 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 reflects 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 supplying electricity for local neighborhood street lamps and 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, mostly because of population, these sources are well distributed throughout North America.

INDUSTRIAL MANUFACTURING

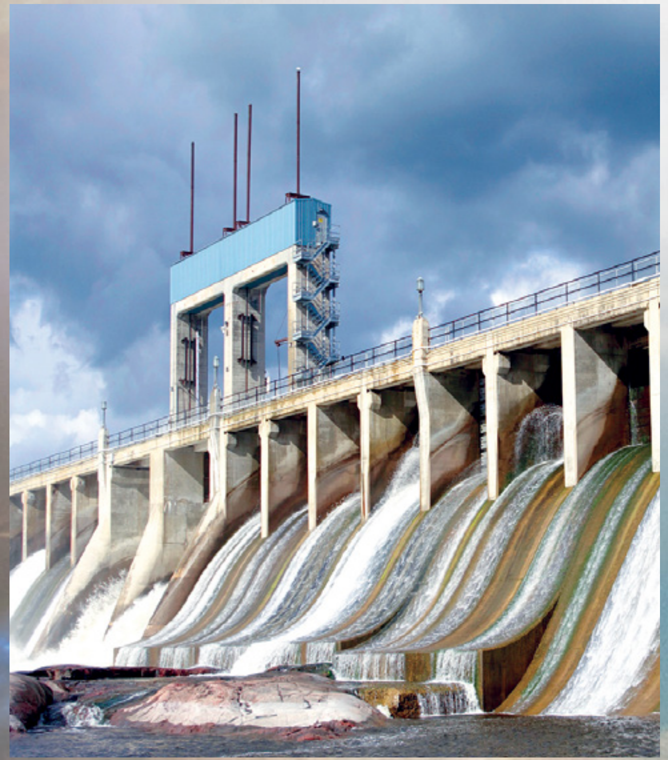
The Great Lakes region in the United States is a robust center of industrial manufacturing. Food processing, iron and steel production, and textile and automotive manufacturing are some of the many activities that consume large quantities of energy and produce significant amounts of CO_2.

FINDING A CO_2 SOLUTION

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 CO_2 released by human activity must be substantially reduced.

A number of techniques can be employed to reduce CO_2 emissions, including conserving energy, 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.

> 41 CCUS facilities are in operation worldwide, capturing 49 million tonnes of CO_2. An additional 26 projects are in construction, and 325 projects are in development.[18]
>
> Global Status of CCS Report 2023



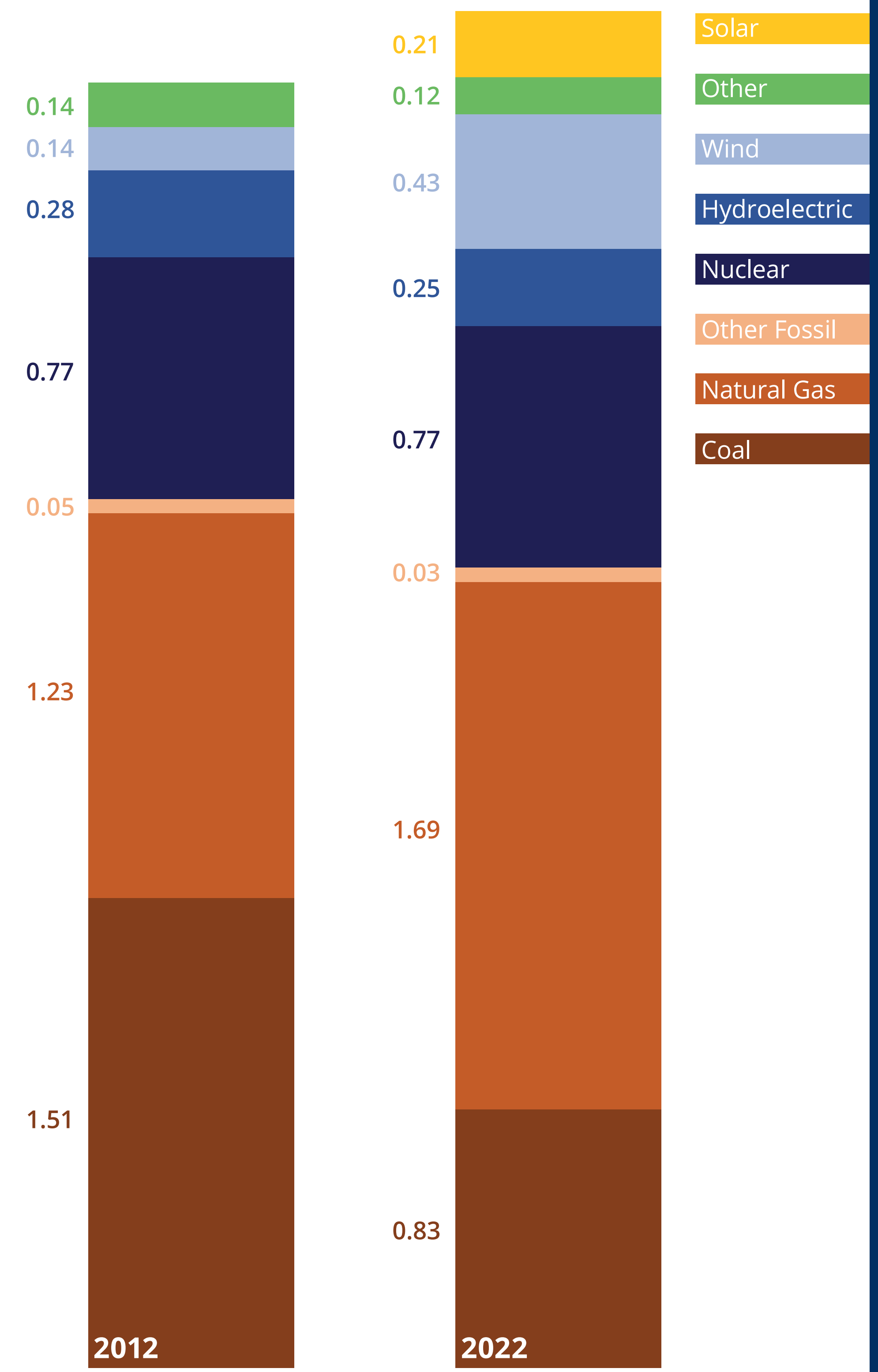
RELIABLE ENERGY MIX

Over the past decade, 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 about 50% from 2012. 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 future low-carbon power generation can evolve without sacrificing resilience and reliability. A 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.[19] Thus CCUS-enabled power production can contribute to energy security while complementing and facilitating the increased deployment of renewables.

U.S. NET ELECTRICITY GENERATION FOR ALL SECTORS[19]
(billion MWh)



Although the total amount of electricity generated for the U.S. grid has remained relatively constant over the last decade, 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 CO_2 emissions from energy production.