MEETING THE DUAL CHALLENGE

A Roadmap to At-Scale Deployment of CARBON CAPTURE, USE, AND STORAGE

CHAPTER ONE – THE ROLE OF CCUS IN THE FUTURE ENERGY MIX

A Report of the National Petroleum Council
December 2019

This chapter was last updated on
March 12, 2021

Chapter One

THE ROLE OF CCUS IN THE FUTURE ENERGY MIX

I. CHAPTER SUMMARY

As global economies and populations continue to grow and prosper, the world faces the dual challenge to deliver affordable, reliable energy while addressing the risks of climate change. Energy fuels the engine of economic growth. For people in developed economies, reliable energy access—used for heat, cooling, light, and mobility—is the expectation. Reliable access is key to high standards of living. Yet for many people in emerging economies, the lack of reliable access to energy limits progress. At the same time, societal concern for the environment, and avoiding the risks of climate change, has led to demand for energy sources with lower emissions.

Lowering emissions will require many measures, such as energy efficiency and increased use of renewable sources of energy (renewables), and a shift to less carbon-intensive fuels. In addition, carbon capture, use, and storage (CCUS)[1] is a critical component of the portfolio of solutions needed to satisfy the dual challenge. Most long-term scenarios show that widespread deployment of CCUS is essential to meet energy delivery goals while reducing greenhouse gas (GHG) emissions[2]—of which carbon dioxide (CO_2) is the most significant—at the lowest cost.

CCUS combines processes and technologies to reduce or remove CO_2 from the atmosphere. It can play a crucial role in helping to reduce emissions from power and industry. Likewise, CCUS supports the deployment of renewables by reducing the emissions of fuels that can mitigate fluctuations in power generation from intermittent wind and solar. CCUS technologies are currently being applied in many industries, including power, steel, hydrogen, fertilizer, ethanol, chemical, and cement.

Many governments around the globe are enacting policies focused on emissions reduction. Stakeholders, including shareholders and non-governmental organizations (NGOs), have taken decisive action to signal their commitment to greater sustainability with CO_2 reduction as a clear goal. And, as consumer awareness grows, people have become more environmentally conscious. Collectively, these movements create new market opportunities. The United States is well positioned to lead entry into these markets due to its experience with CCUS projects, established regulatory framework, world-leading policy support, cutting-edge research capability, and an innovative business climate.

II. THE WORLD NEEDS MORE ENERGY TO SUPPORT AN INCREASE IN POPULATION AND A GROWING GLOBAL ECONOMY

Over the next two decades, global population is expected to increase by about 1.5 billion people, reaching approximately 9.2 billion by 2040.[3] This increase is more than four times the population of the United States in 2019. At the same time,

1 CCUS includes transport.

2 For the purposes of this study, GHGs include CO_2, methane, nitrous oxide (N_2O), ozone, and chlorofluorocarbons.

3 United Nations, Department of Economic and Social Affairs, Population Division. (2019). *World Population Prospects 2019,* Online Edition. Rev. 1.

the world economy is expected to surge as gross domestic product (GDP) more than doubles. Such an expansion of global prosperity will lift billions in the developing world from low to middle incomes. This surge in global living standards is expected to increase energy consumption.

In its Energy Poverty Action Initiative, the World Economic Forum recognized that, "Access to energy is fundamental to improving quality of life and is a key imperative for economic development." Figure 1-1 illustrates this relationship, comparing the United Nations Human Development Index—an assessment of life expectancy, education levels, and gross national income per capita—to energy use per capita. The data suggests that as energy use per capita rises, quality of life increases significantly, and the relationship flattens out at about 100 gigajoules (GJ) per capita per year.[4]

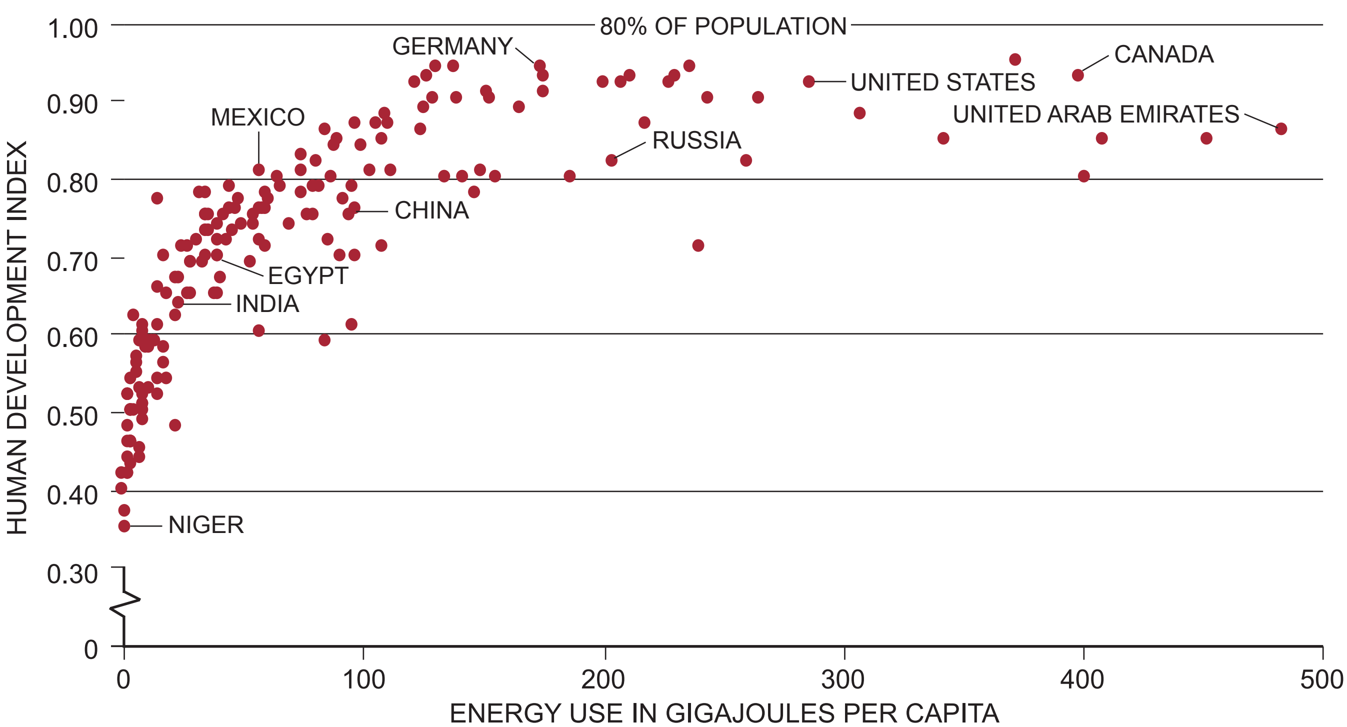
4 *BP Energy Outlook*. (2019). London, UK: BP p.l.c., https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/energy-outlook/bp-energy-outlook-2019.pdf.

Eighty percent of the world's population lives in countries where per capita energy consumption is less than 100 GJ per year, and the global average in 2017 was only 82 GJ. In comparison, the average annual energy consumption for members of the Organization for Economic Co-operation (OECD) is about 169 GJ.[5] This pronounced difference in consumption—more than double the global average—highlights the gap between most OECD countries and developing economies.

To help define the nature of the energy system, many institutions have projected pathways for the evolution of energy demand and supply. These assessments rely on a range of assumptions, which can vary widely between scenarios and organizations. Many outlooks expect global demand for energy to grow by 25% to 30% by 2040.[6]

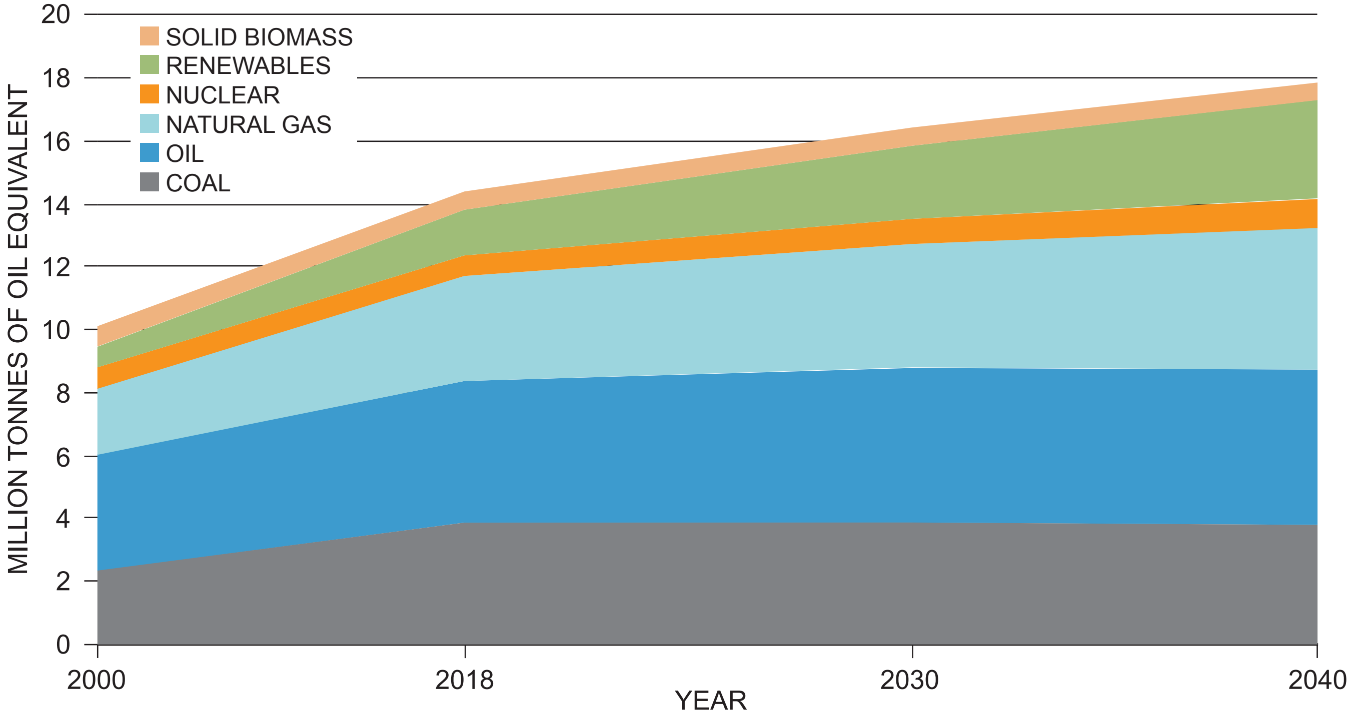
5 The OECD average excludes Iceland because it was not included in the data set.

6 *BP Energy Outlook* (2019); ExxonMobil, *Outlook for Energy* (2019); International Energy Agency, *World Energy Outlook 2019,* Stated Policies Scenario.



Source: 2017 United Nations Human Development Index and BP Energy Outlook 2019.

Figure 1-1. *2017 Human Development Index and Energy Consumption per Capita*



Source: Based on data from International Energy Agency, World Energy Outlook 2019.

Figure 1-2. *IEA Stated Policies Scenario Shows More Than a 25% Increase in Global Primary Energy Demand by 2040*

This is true for the International Energy Agency's (IEA) Stated Policies Scenario (STEPS[7,8]), which aims "to provide a detailed sense of the direction in which existing policy frameworks and today's policy ambitions would take the energy sector out to 2040."[9,10] Figure 1-2 shows that the STEPS estimates global energy demand will rise more than 25% by 2040. Most of this growth will come from India and China, as well as other emerging economies, as prosperity and populations rise. Conversely, as energy efficiency improves, demand in many developed economies, like the United States, is expected to remain flat or decline. (See also text box titled "Three Views on U.S. Energy Consumption.")

III. THE WORLD WILL NEED TO ADDRESS THE RISKS OF CLIMATE CHANGE

In addition to providing more affordable, reliable energy to support growing economies and populations, the world will need to address rising GHG emissions and the risks of climate change. In 2019, atmospheric concentrations of CO_2 climbed to over 400 parts per million (ppm) from a pre-Industrial Revolution level of 280 ppm.[11]

According to the Intergovernmental Panel on Climate Change (IPCC), "It is extremely likely that more than half of the observed increase in

7 "Previously known as the New Policies Scenario, it has been renamed to underline that it considers only specific policy initiatives that have already been announced. The aim is to hold up a mirror to the plans of today's policy makers and illustrate their consequences, not to guess how these policy preferences may change in the future." Source: International Energy Agency. (2019). *World Energy Outlook,* Executive Summary, p. 23.

8 "STEPS: the Stated (Energy) Policies Scenario." Source: International Energy Agency (2019) *World Energy Outlook,* Introduction, p. 29.

9 International Energy Agency. (2019). *World Energy Outlook,* https://www.iea.org/weo/weomodel/steps/.

10 On page 6 of *Facing the Hard Truths about Energy Executive Summary* (2007), the National Petroleum Council noted that, "Policies aimed at curbing CO_2 emissions will alter the energy mix, increase energy-related costs, and require reductions in demand growth." This point is also supported by the Intergovernmental Panel on Climate Change, IEA, and other global entities.

11 *Data Snapshots: Reusable Climate Maps,* National Oceanic and Atmospheric Administration, Climate.gov, https://www.climate.gov/maps-data.

THREE VIEWS ON U.S. ENERGY CONSUMPTION

In contrast to global demand, U.S. energy demand is expected to remain flat or decline in the next two decades. The figure below shows three projections for U.S. energy demand in 2040.

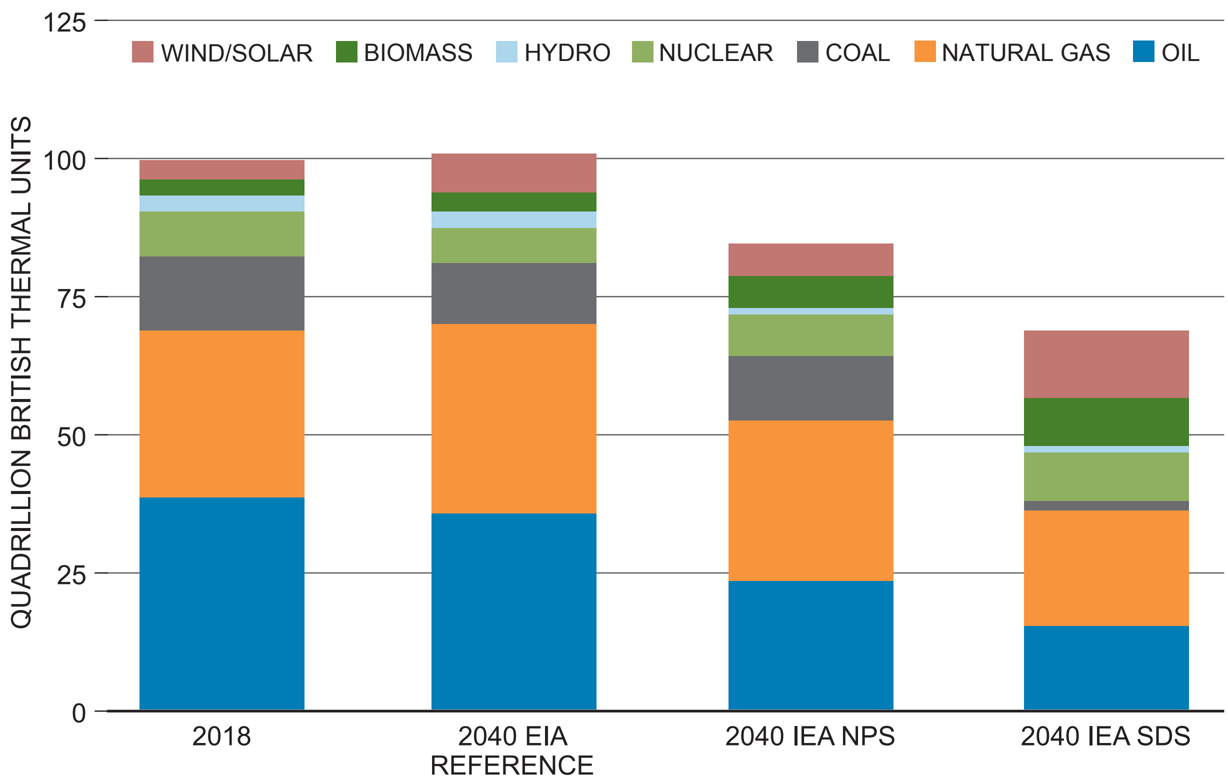
The U.S. Energy Information Administration's reference case—which does not include new greenhouse gas reduction policies—projects that energy demand in 2040 will be flat with the level in 2018.*

The International Energy Agency's Stated Policies Scenario (STEPS), previously known as the New Policies Scenario (NPS), which includes energy policies that stem from governments' announced intentions, shows U.S. primary energy demand decreasing about 16% by 2040.

Finally, the IEA Sustainable Development Scenario (SDS), which makes assumptions to hold the average global temperature increase to well below 2°C, shows U.S. primary energy demand in 2040 shrinking by about 31% compared with 2018 levels.

To meet these scenario demands at the lowest cost, the STEPS and SDS include policies and emissions constraints that lead to deployment of efficiency measures and zero-emissions technologies, including wind, solar, nuclear, and CCUS.

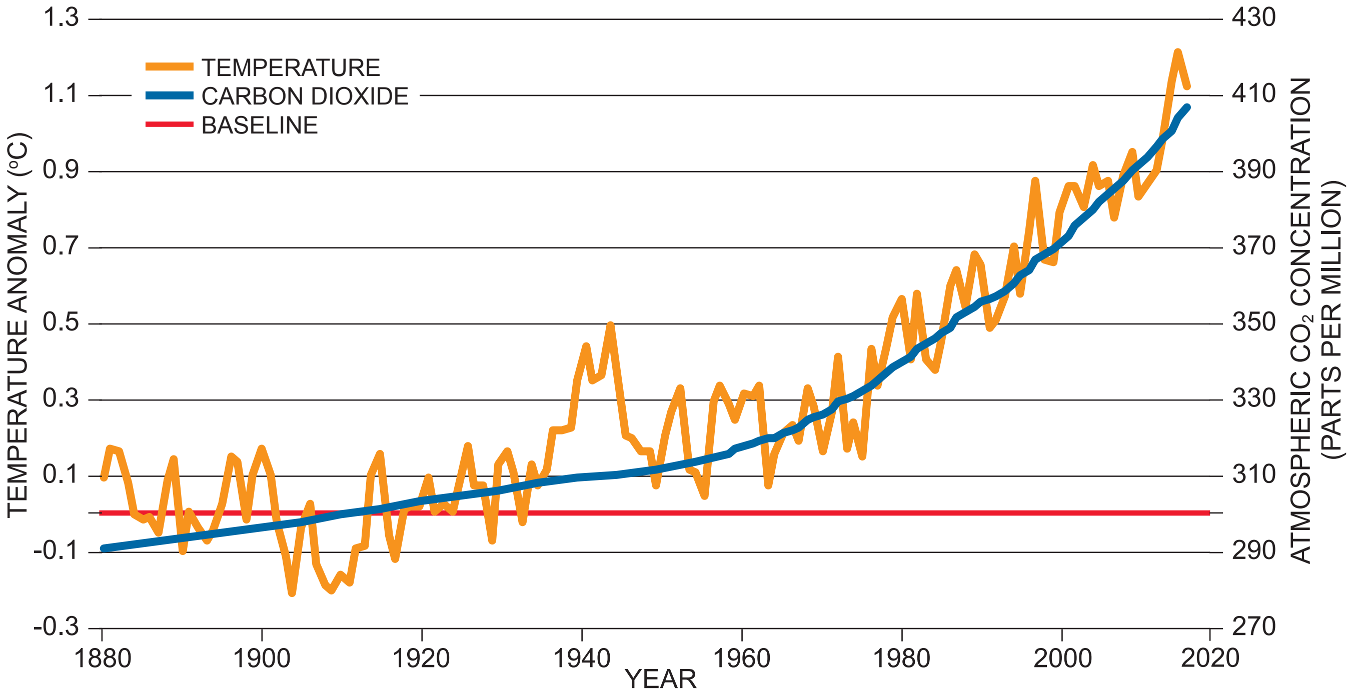
* EIA, *Annual Energy Outlook 2019 with Projections to 2050.* Washington, D.C.: U.S. Energy Information Administration, 2019. www.eia.gov/aeo, accessed December 2, 2019.



Note: "Consumption" as used here does not include net exports, such as export of LNG.

Source: The IEA New Policies Scenario and Sustainable Development Scenario are based on IEA data from International Energy Agency, *World Energy Outlook* 2018; as modified by the National Petroleum Council.

U.S. Energy Consumption by Type



Note: Global temperature anomalies averaged and adjusted to early industrial baseline (1881-1910).
Source: Climate Central, "Rising Global Temperatures and CO_2," November 20, 2018.

Figure 1-3. *The Relationship between CO_2 Concentration and Global Temperature*

global average surface temperature from 1951 to 2010 was caused by an anthropogenic[12] increase in greenhouse gas concentrations,"[13] and "continued emission of greenhouse gases will cause further warming and long-lasting changes in all components of the climate system."[14] Figure 1-3 shows the relationship between CO_2 concentration and global temperature. (See also text box titled "CO_2 and the Greenhouse Effect.")

IV. WHAT IS CCUS?

CCUS combines several technologies to reduce the level of CO_2 emitted to the atmosphere. The CCUS process, as shown in Figure 1-4, involves the capture (separation and purification) of CO_2 from stationary sources so that it can be transported to a suitable location where it is converted into useable products or injected deep underground for safe, secure, and permanent storage.

Although CCUS supply chains can have many forms, the building blocks are generally described as follows:

Capture. CO_2 is produced in combination with other gases during industrial processes, including hydrocarbon-based power generation. CO_2 capture involves the separation of the CO_2 from these other gases. This separation can be accomplished using many different technologies, the most common of which is amine absorption. Once the CO_2 is separated, it is typically compressed or refrigerated so that it behaves like a liquid, making it ready for transport and storage.

Transport. In most cases, captured CO_2 will need to be transported from the capture location to a different location where it can be used

12 From *Merriam-Webster*—anthropogenic (adjective): of, relating to, or resulting from the influence of human beings on nature.

13 IPCC, 2013: *Climate Change 2013: The Physical Science Basis. Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, p. 17.

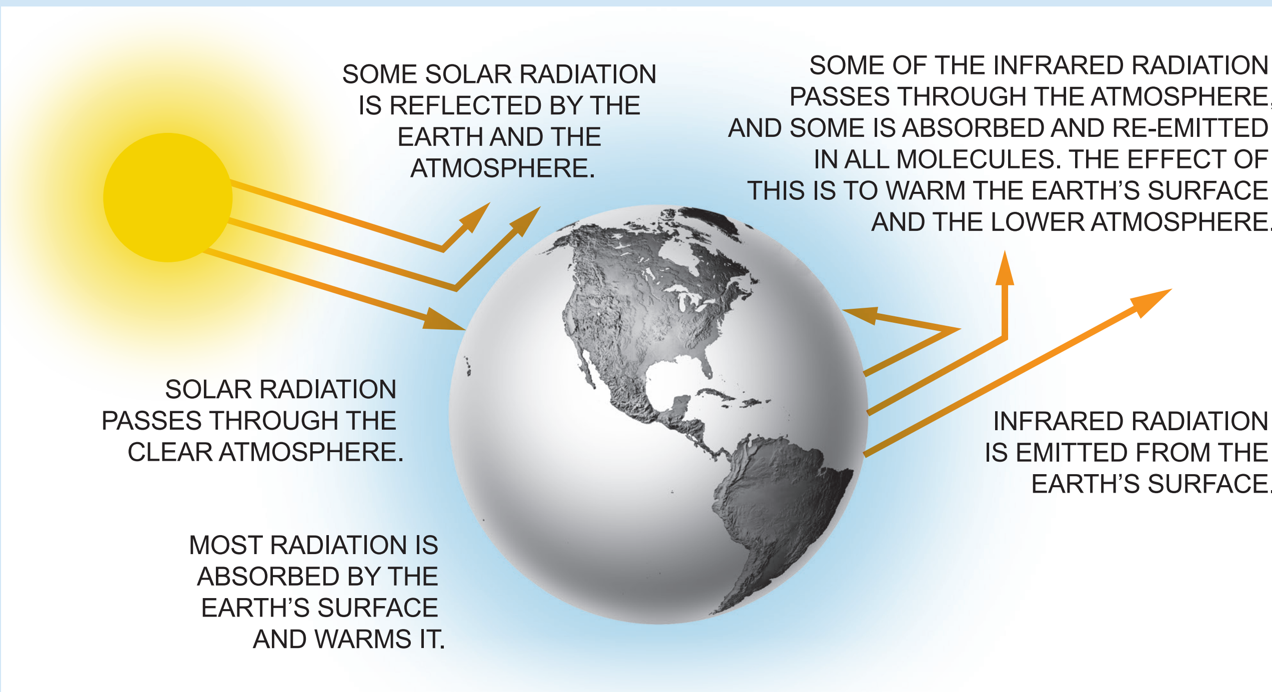
14 IPCC, 2014: *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, p. 8.

CO_2 AND THE GREENHOUSE EFFECT

CO_2 is a colorless, odorless, incombustible gas that is primarily produced through human activities—the combustion of hydrocarbon products (coal, oil, natural gas) and from certain industrial processes (production of cement, steel, chemicals). It also occurs through natural processes, like the respiration of animals and humans, and is absorbed by plants through photosynthesis. CO_2 is the largest contributor to climate change from human activities, and once generated, remains in the environment until it is proactively removed.

The greenhouse effect is an atmospheric process that warms the Earth's surface. As solar energy enters the atmosphere, it is either reflected back to space (often by clouds or ice) or absorbed by the Earth's surface. The Earth also emits energy as infrared radiation that travels directly to space or is absorbed by atmospheric gases and remains as heat. Greenhouse gases (GHGs) include CO_2, methane, nitrous oxide (N_2O), ozone, and chlorofluorocarbons; they permit sunlight to enter the atmosphere but trap heat before it escapes (see figure below). Without the greenhouse effect, Earth's temperature would fall to -18°C.

Over time, economic development has increased the amount of GHGs in the atmosphere and intensified the natural greenhouse effect, resulting in an increased global average temperature. Reducing CO_2 emissions and removing CO_2 from the atmosphere are two methods that can help lower the increase in global temperature. CCUS technologies can support both pathways.



Source: EIA, "Energy and the Environment Explained," July 11, 2019.

The Greenhouse Effect

or stored. This transport is typically accomplished using pipelines operating at a pressure that enables the CO_2 to remain compressed into a dense liquid phase. This compressed CO_2 can also be transported by rail, truck, ship, and barge.

Use. Although the majority of captured CO_2 is stored, it can also be used to create other products, such as building materials and carbon fiber tubes. Despite the relatively small amount of captured CO_2 that is used for other purposes,

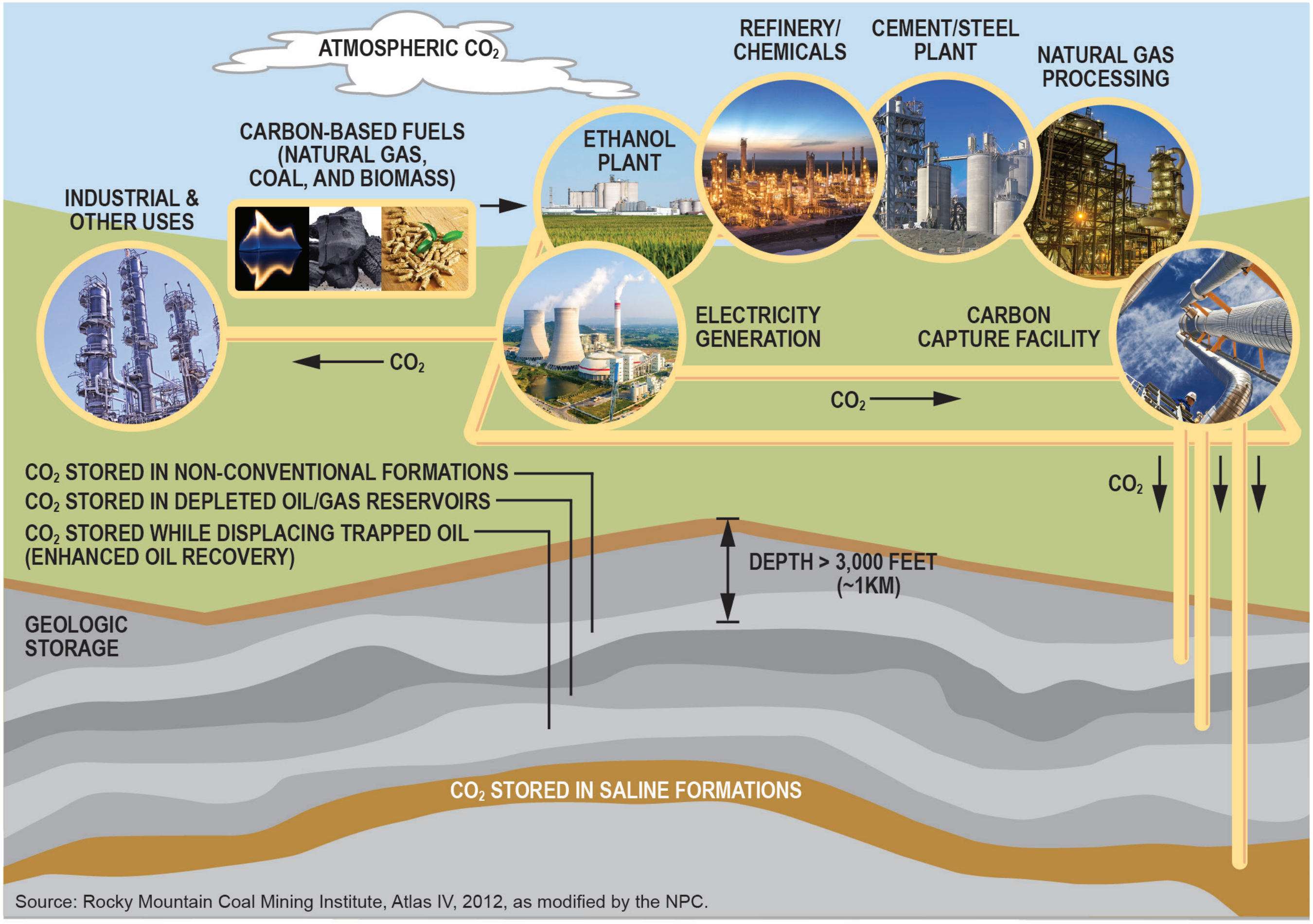


Figure 1-4. *Supply Chain for Carbon Capture, Use, and Storage*

market and technology development might provide several economically viable opportunities to increase its use.

Storage. Safe, secure, and permanent storage of compressed CO_2 occurs by injecting it into carefully selected subsurface geologic formations. These are usually saline formations, depleted oil and gas reservoirs, and un-mineable coal seams. CO_2 is also used to produce oil via a process called enhanced oil recovery (EOR). Operational experience indicates that approximately 99% of the CO_2 used in EOR is ultimately trapped in hydrocarbon-producing geologic formations.

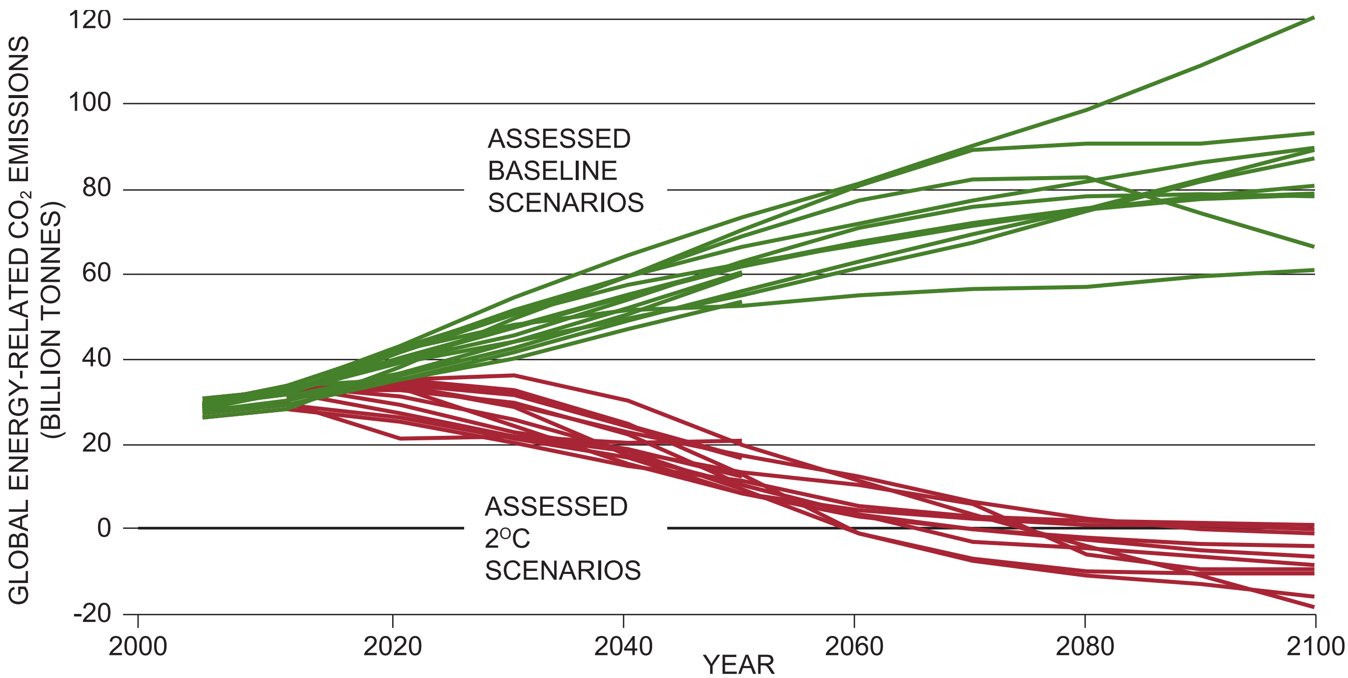
V. THE ROLE OF CCUS

CCUS is an essential element in the portfolio of solutions needed to change the emissions trajectory of the global energy system. In its *Fifth Assessment Report,* the IPCC concluded that the costs for achieving atmospheric CO_2 levels consistent with holding average global temperatures to 2°C above preindustrial levels—referred to as a "2°C world"—will be more than twice as expensive without CCUS.[15]

In support of that report, the Energy Modeling Forum 27 at Stanford University evaluated various scenarios with specific stabilization targets consistent with a 2°C world that would, for example, limit atmospheric CO_2 to 450 ppm.[16] As part of that work, Figure 1-5 presents potential

15 IPCC, 2014: *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp. in IPCC ARS Synthesis Report website.

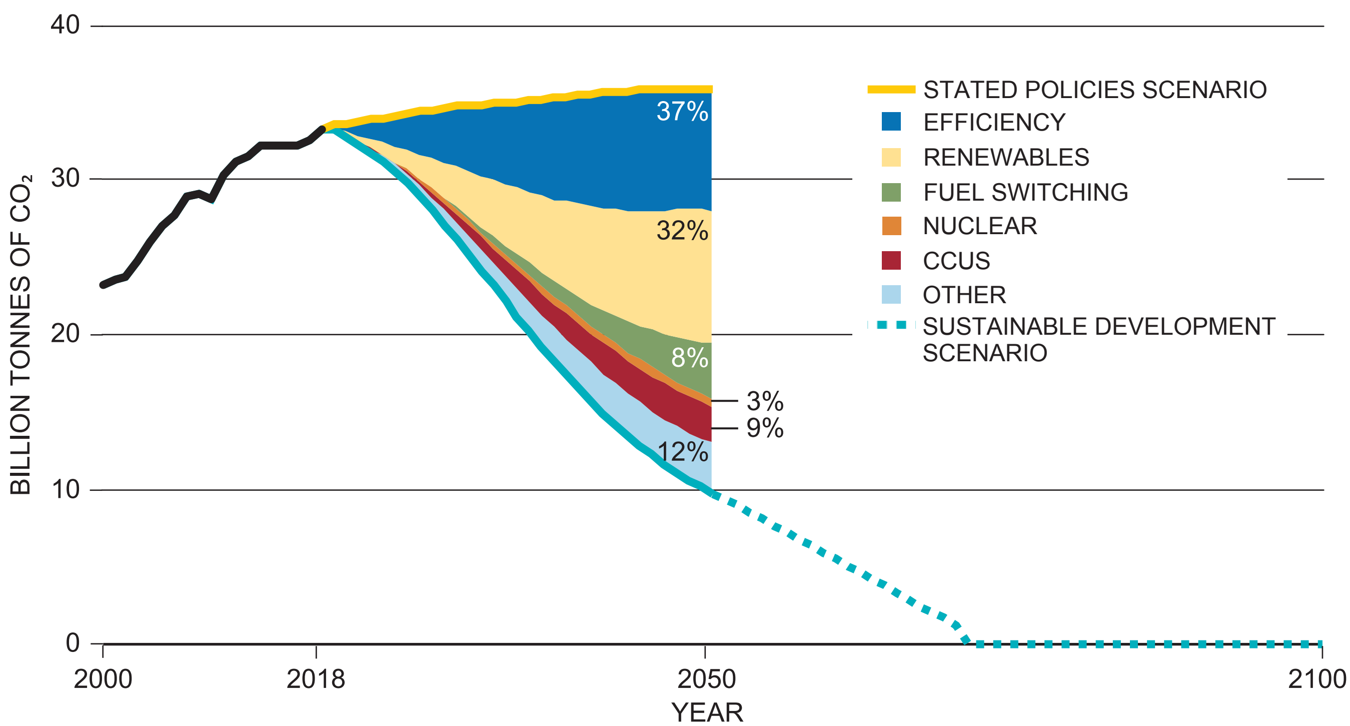
16 *2019 Outlook for Energy: A Perspective to 2040.* Irving, TX: ExxonMobil Corporation, 2019, https://corporate.exxonmobil.com/-/media/Global/Files/outlook-for-energy/2019-Outlook-for-Energy_v4.pdf.



Notes: Assessed scenarios included CO_2 emissions from energy and industrial processes.
Assessed scenarios refer to EMF27 baseline and 450 ppm full technology scenarios.

Source: ExxonMobil Outlook for Energy, 2019.

Figure 1-5. *Comparison of Assessed Baseline and 2°C Scenarios to Achieve Global Net-Zero Emissions by 2100*



Source: Based on data from International Energy Agency, World Energy Outlook 2019.

Figure 1-6. *Global Emissions Projections for the IEA's Stated Policies Scenario and Sustainable Development Scenario* outlooks for global energy-related CO_2 emissions under different stabilization scenarios (assessed 2°C scenarios) relative to baseline scenarios that represent pathways with limited change in policy.

The set of baseline scenarios shows CO_2 emissions growing steadily until 2100. The assessed 2°C scenarios show that global CO_2 emissions must decline to zero and, in most cases, become negative in the second half of the century. To achieve these reductions, the assessed 2°C scenarios require processes that remove CO_2 from the atmosphere. These CO_2 removal technologies enable "negative emissions."

Bioenergy with CCUS (BECCS) and direct air capture (DAC) are two negative emissions processes that could be applied to achieve a 2°C world. The BECCS process converts biomass, which extracts CO_2 from the atmosphere as it grows, to energy and the resulting CO_2 is captured and geologically stored. The DAC process captures CO_2 from the air to create purified CO_2 for use or storage.

The IEA forecasts the role of CCUS in its Sustainable Development Scenario (SDS). Figure 1-6 depicts the difference in global emissions projections between the IEA STEPS and SDS. In the SDS, CCUS contributes 9% of cumulative emissions reductions globally by 2050, making it a vital part of the mix of solutions needed to reach SDS targets.[17]

As the IEA explained in 2017, "Our analysis consistently shows that CCUS is a critical part of a complete clean energy technology portfolio that provides a sustainable path for mitigating greenhouse gas emissions while ensuring energy security."[18] The rationale supporting CCUS as a part of a global clean energy technology portfolio is related, in part, to historical energy demand and expected energy demand growth in Asia. In September 2019, German environmental organization Urgewald estimated that China and India would account for more than half of new planned coal-fired power plants around the world.[19,20] Without retrofitting CCUS to these long-lived energy assets (up to 40 to 50 years[21]), achieving the SDS goals may require premature retirement of these facilities.

VI. NEW MARKETS ARE EMERGING AS THE WORLD TRANSITIONS TO A LOWER-CARBON ENERGY SYSTEM

The Industrial Revolution in the late 18th and early 19th centuries sparked technological breakthroughs and created new industries. As manufacturing expanded and innovation improved, labor-intensive processes, energy demand, and GDP per capita soared. The advancements in energy delivery and utility—unlocked by fossil fuel combustion—transformed the global energy system.

More than 200 years later, fossil fuels are deeply woven into the current energy and consumer product supply chains, accounting for about 80% of both the United States and global fuel mix. Beyond heat, light, and mobility, fossil fuels are the building blocks for a vast array of petrochemical products such as plastics, lubricants, and fabrics. They also enable the production of key building materials like cement and steel.

17 The SDS "sets out the major changes that would be required to reach the key energy-related goals of the United Nations Sustainable Development Agenda. These are:

An early peak and rapid subsequent reductions in emissions, in line with the Paris Agreement (Sustainable Development Goal [SDG] 13).

Universal access to modern energy by 2030, including electricity and clean cooking (SDG 7).

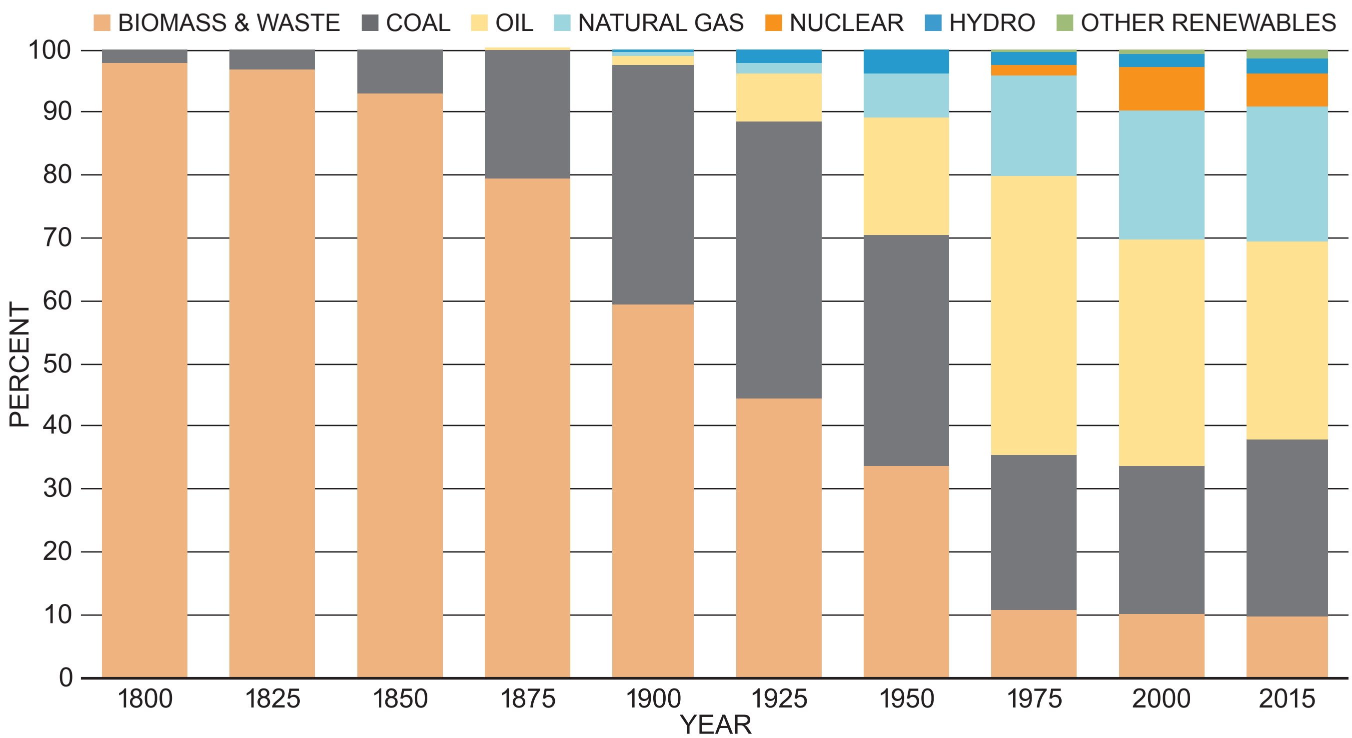
A dramatic reduction in energy-related air pollution and the associated impacts on public health (SDG 3.9)."

18 International Energy Agency. (2017). "IEA and China Host High-Level Gathering of Energy Ministers and Industry Leaders to Affirm the Importance of Carbon Capture," https://www.iea.org/newsroom/news/2017/june/iea-and-china-host-high-level-gathering-of-energy-ministers-and-industry-leaders.html.

19 Planned coal-fired power plants tallied 579 gigawatts (GW) of which China and India planned 226 GW and 92 GW, respectively.

20 Witkop, N., "China behind Bulk of World's Coal Growth Plans – Report." Montel News, September 19, 2019. https://www.montelnews.com/en/story/china-behind-bulk-of-worlds-coal-growth-plans--report/1044193.

21 "Why Is China Placing a Bet on Coal?" *Morning Edition: NPR*. Washington, D.C.: National Public Radio, April 29, 2019, https://www.npr.org/2019/04/29/716347646/why-is-china-placing-a-global-bet-on-coal.



Source: Resources for the Future. (2019). Global Energy Outlook data tool. Accessed via www.rff.org/geo.

Figure 1-7. *Global Primary Energy Demand by Share*

Figure 1-7 illustrates global primary energy demand by share. In the chart, the label "other renewables" includes solar, wind, and geothermal. Hydropower and traditional biofuels are listed in separate categories. Throughout history, it has taken decades for new energy sources to achieve a substantial market share. However, to meet the dual challenge, the world will need a greatly accelerated transition to a lower-carbon energy system.

Until the mid-20th century, availability and cost were the primary drivers for consumers' energy choices. Over time, the environmental impacts of energy production and consumption have become a concern. In the 1980s, air and water pollution became a concern in the United States when smog and acid rain caused adverse impacts. Government and industry collaborations, combined with government regulations, yielded successful reductions in those pollutants.

Over the past few decades, the public has placed greater emphasis on the environment and climate change. In response, many governments have enacted policies to reduce emissions, leading to widespread deployment of lower CO_2-intensive technologies. In the United States, durable policy frameworks helped create markets for energy sources with lower emissions. In 2018, wind, biofuels, and solar accounted for 5.5% of U.S. primary energy consumption.[22]

Some governments have embraced carbon pricing to reduce emissions. As of September 2019, there were 57 carbon pricing initiatives—comprising both emissions trading systems (ETS) and carbon taxes—implemented or scheduled for implementation worldwide (Figure 1-8) that address 11 gigatonnes of CO_2 equivalent, or about 20% of global GHG emissions per year. Furthermore, in the Nationally Determined Contributions (NDCs) under the Paris Agreement, 100 countries consider carbon pricing to meet their emissions reduction ambitions.[23]

22 *2019 Annual Energy Outlook with Projections to 2050,* Washington, D.C.: U.S. Energy Information Administration, 2019, https://www.eia.gov/aeo.

23 2019 United Nations Framework Convention on Climate Change: "What does the Paris Agreement say on carbon pricing? https://unfccc.int/about-us/regional-collaboration-centres/the-ci-aca-initiative/about-carbon-pricing#eq-7.

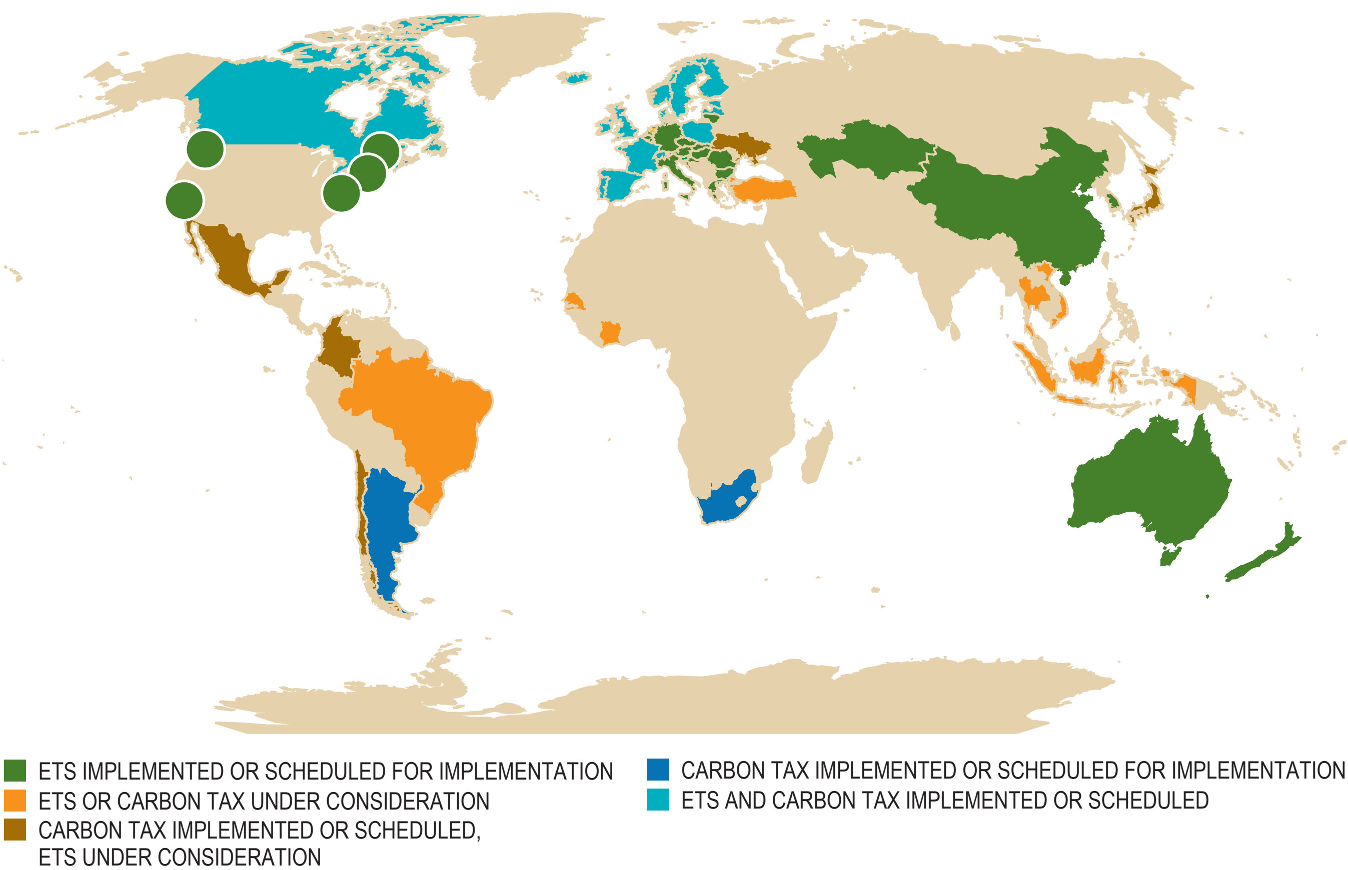
Beyond carbon pricing, 13 entities—including China, Japan, and the European Union—have incorporated CCUS in their NDCs/low-carbon road maps.[24] Some governments are looking to standards, mandates, and financial incentives to decarbonize.

Some governments recognize the potential for CCUS to decarbonize heavy industry.[25] Countries in the European Union have identified industrial clusters suitable for CCUS deployment, including the Port of Rotterdam's CO_2 Transport Hub and Offshore Storage (PORTHOS) project in the Netherlands, Northern Lights in Norway, and five low-carbon clusters in the United Kingdom—Humber, Merseyside, North East Scotland, South Wales, and Teesside.

Lower carbon markets continue to emerge in the United States. Figure 1-9 illustrates the policies and incentives promoting energy efficiency and renewable energy by state. This activity demonstrates the country's broad interest in addressing the risks of climate change through mechanisms, including renewable energy, low-carbon fuel standards, and energy efficiency. One of the most recent and impactful policies implemented at the federal level is the 45Q tax credit. In total, there are more than 3,500 policies and incentives at the local, state, and federal levels. Chapter 3, "Policy, Regulatory, and Legal Enablers," outlines the details of various policy mechanisms.

24 2019 United Nations Framework Convention on Climate Change, "The Paris Agreement and NDCs": https://unfccc.int/process/the-paris-agreement/nationally-determined-contributions/ndc-registry.

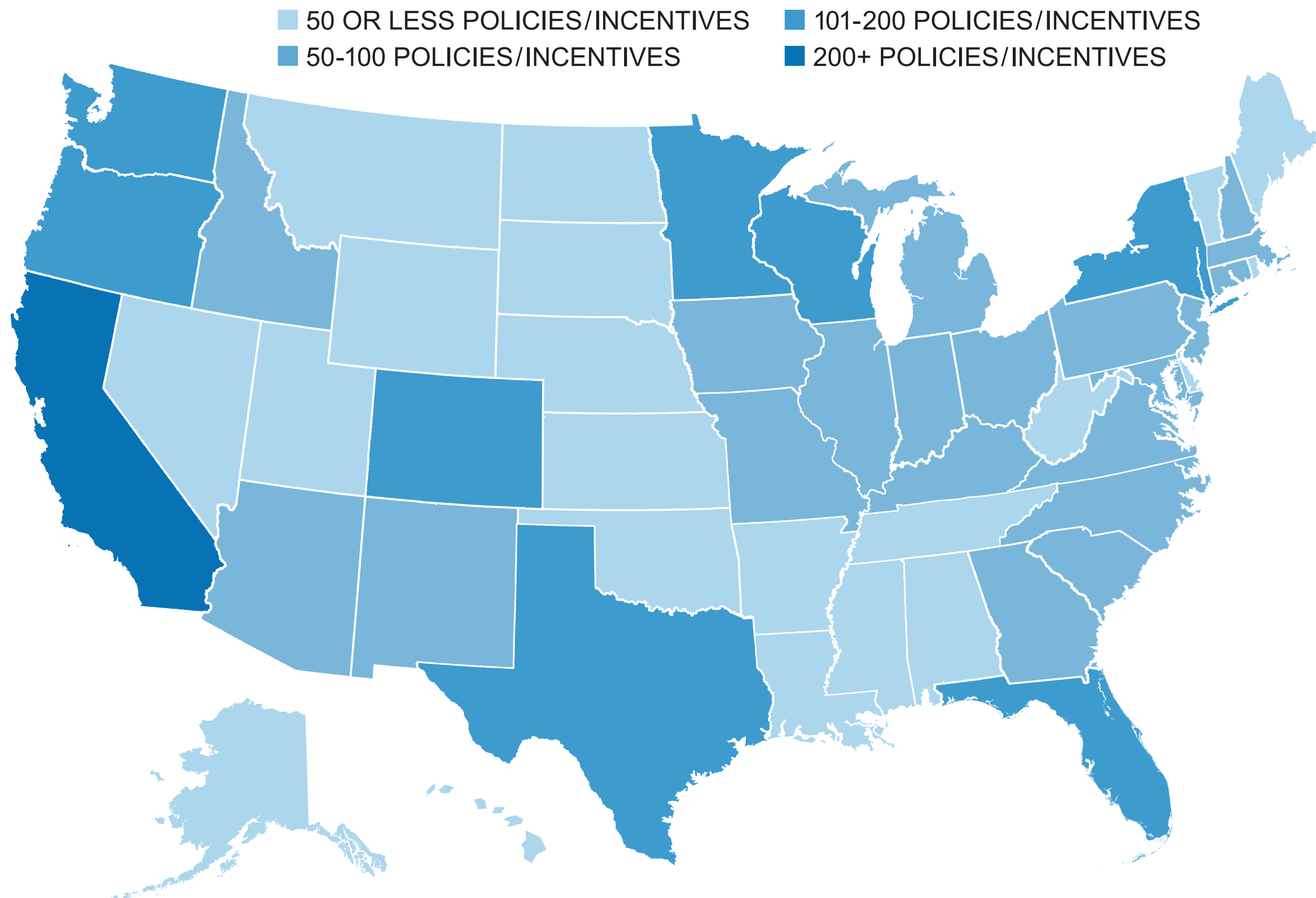
25 International Energy Agency. (2019). "Transforming Industry through CCUS," IEA, Paris, https://www.iea.org/publications/reports/TransformingIndustrythroughCCUS/.



Note: The circles on the map represent cooperation initiatives on carbon pricing between subnational jurisdictions.

Source: The World Bank, Carbon Pricing Dashboard, August 1, 2019.

Figure 1-8. *Countries That Have Implemented or Scheduled Implementation of Carbon Pricing*



Source: Database of State Incentives for Renewables & Efficiency (DSIRE) from the N.C. Clean Energy Technology Center.

Figure 1-9. *Clean Energy Policies and Incentives by State in November 2019*

Sustained societal expectations and government action to lower GHG emissions will continue to create opportunities for technology development and new markets, particularly for CCUS. International collaboration will be key as global interest and markets grow. For example, the United States, United Kingdom, Norway, and Saudi Arabia established a CCUS initiative under the Clean Energy Ministerial process to include CCUS technologies in clean energy discussions on a regular basis. The initiative now has 11 member countries[26] and works to bring governments, industry, and the financial community together to accelerate CCUS project deployment.

The United States is uniquely positioned to compete in this global market by exporting the world-leading technologies and expertise it has already gained through the 10 large-scale CCUS projects within its borders, which is more than any other country in the world. The United States would increase its competitiveness in the global market by continued development of its domestic capabilities and resources through at-scale deployment of CCUS. A description of U.S. leadership in CCUS is described in Chapter 2, "CCUS Supply Chains and Economics."

In 2014, EOR projects in the United States used CO_2 to produce approximately 300,000 barrels of oil per day—more than 2% of U.S. oil production.[27] By expanding the use of CO_2 for EOR through further development of domestic resources, the United States can sustain and protect its energy

26 Members include Canada, China, Japan, Mexico, Netherlands, Norway, Saudi Arabia, South Africa, United Arab Emirates, UK, and the United States.

27 Kuuskraa, V., and Wallace, M., "CO_2 – EOR set for growth as new CO_2 supplies emerge." *Oil & Gas Journal,* Pennwell, April 7, 2014, https://www.adv-res.com/pdf/CO2-EOR-set-for-growth-as-new-CO2-supplies-emerge.pdf.

security. Increased production also creates economic benefits for businesses, local communities, and states, and it helps maintain and expand the jobs and capabilities associated with oil and natural gas production. Additionally, EOR has a relatively small environmental footprint because existing infrastructure and brownfields are often used to produce incremental oil. A 2015 study by the IEA estimated that oil produced through EOR is 63% less carbon intensive than oil produced through traditional methods.[28]

There may also be an opportunity for the United States to market its CO_2 storage resources to countries that do not have favorable geology for such storage. Because the volume of subsurface CO_2 storage potential in the United States greatly exceeds the capacity likely to be used by U.S. sources, there could be value in importing and storing CO_2 from countries with insufficient storage resources. For example, CO_2 import and storage along the Gulf Coast could become a parallel market to natural gas exports for liquefied natural gas. This concept is like the Northern Lights project being developed in Norway with a goal to create a CO_2 transport and storage system to receive CO_2 originating from a range of industrial sources.

Other potential opportunities may exist in the development and export of low-carbon and decarbonized products, as well as the use of CO_2 as a feedstock. This market is expected to grow based on what is anticipated to be an increase in consumer demand for low-carbon products. Although many of these new products are still in early stages of development, there is an opportunity for the United States to be a leader in commercializing new uses of CO_2.

VII. CCUS CAN CREATE ENVIRONMENTAL BENEFITS FOR THE UNITED STATES THROUGH CO_2 EMISSIONS REDUCTION

On average, U.S. energy-related CO_2 emissions have declined over the last decade.[29] Switching from coal to natural gas in power generation, increased renewable electricity production, and vehicle efficiency gains have all played a role in emissions reduction. The U.S. EIA projects that U.S. energy-related CO_2 emissions will remain essentially unchanged for the next 30 years under current policies (Figure 1-10). The CCUS process and its technologies provide a solution for reducing stationary, or point-source, emissions—those that originate from single, fixed sources like factories, power plants, and refineries. At-scale deployment of CCUS in the United States can enable a dramatic reduction in emissions.

The left side of Figure 1-11 explores U.S. CO_2 emissions by sector. Transportation—travel by air, car, rail, heavy trucking, and shipping—is the largest contributor of U.S. CO_2 emissions.[30] However, these emissions sources are mobile and cannot be significantly decarbonized by current CCUS technologies. This sector is more likely to employ other emissions reduction technologies, such as electrification, efficiency gains, increased use of biofuels, and, potentially, the development of hydrogen as a fuel.[31]

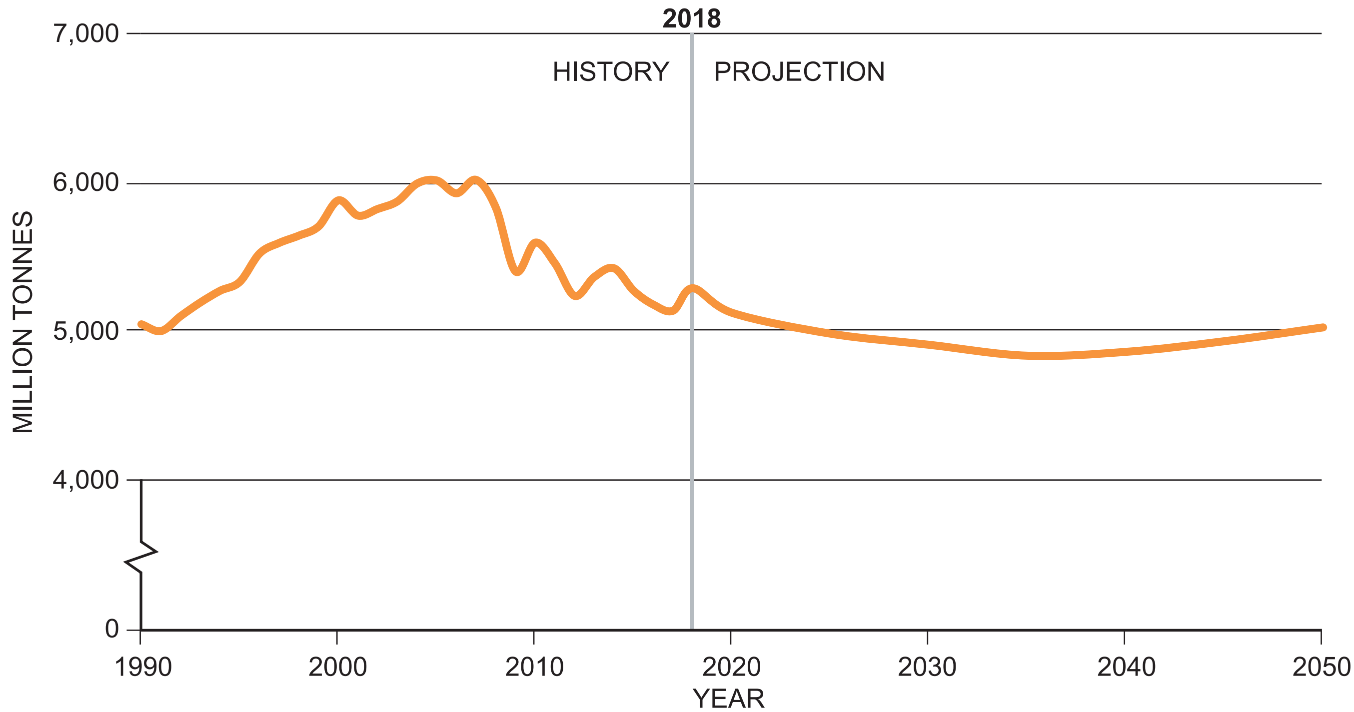
Stationary emission sources from industrial and power generation facilities represent nearly 50% of total U.S. CO_2 emissions. The United States has more than 6,500 large stationary sources emitting approximately 2.6 billion tonnes of CO_2 per year across a range of industries. The right side of Figure 1-11 breaks down U.S. stationary emissions by industry type. Point-source emissions from electricity generation account for more than two-thirds of stationary source CO_2 emissions. Process emissions associated with various industries contribute most of the balance, led by refining and followed by pulp and paper, chemical manufacturing, cement and concrete, and iron and steel manufacturing. These stationary sources are prime candidates for CCUS deployment.

28 International Energy Agency, Insights Series – 2015, Storing CO_2 through Enhanced Oil Recovery, November 3, 2015.

29 It is noteworthy that in 2018 emissions rose, indicating that emissions reduction is not inevitable and may prove difficult.

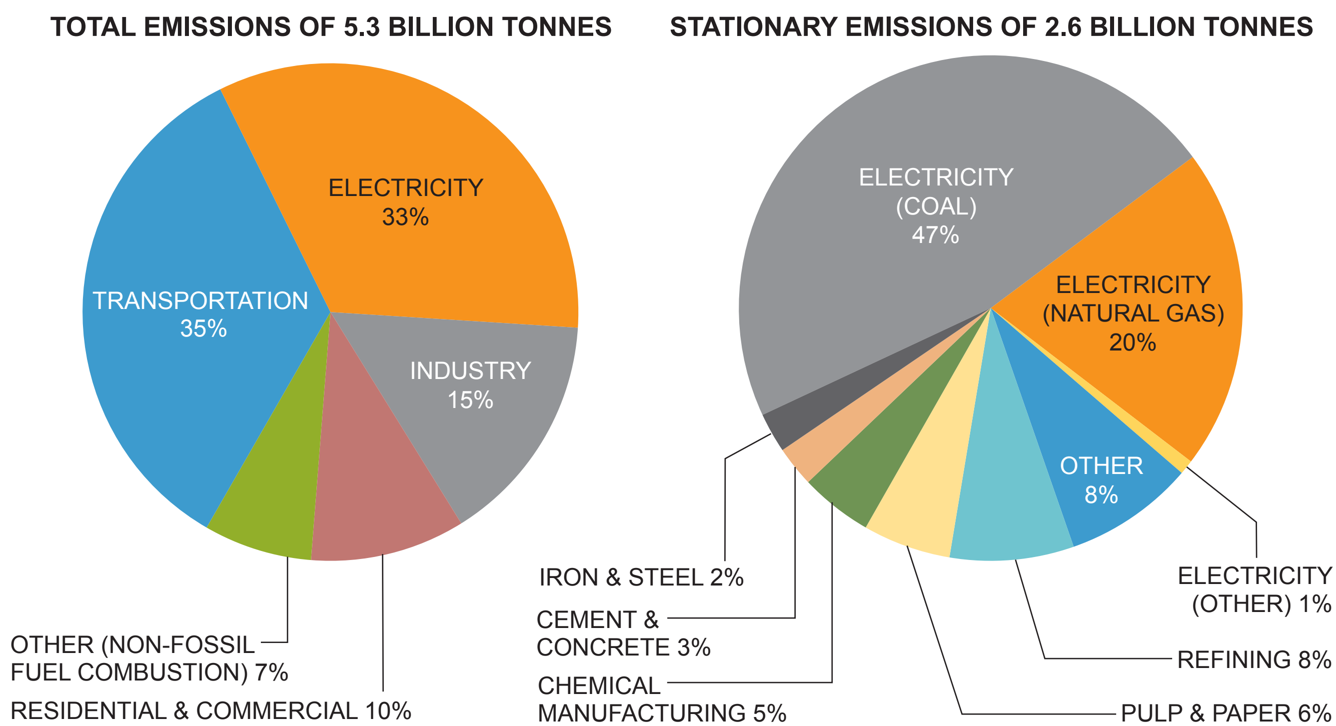
30 U.S. EPA's Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2017, https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks.

31 Energy Transitions Commission, *Mission Possible: Report Summary,* November 2018, p. 10, http://www.energy-transitions.org/sites/default/files/ETC_MissionPossible_ReportSummary_English.pdf.



Source: EIA *Annual Energy Outlook 2019.*

Figure 1-10. *U.S. Energy-Related CO_2 Emissions in AEO2019 Reference Case, 1990 to 2050*



Source: U.S. EPA, Greenhouse Gas Emissions 1990-2017 Inventory Report.

Figure 1-11. *2017 U.S. Energy-Related CO_2 Emissions by Sector (left) and Stationary CO_2 Emissions by Industry Type (right)*

VIII. MANY REGIONS CAN BENEFIT FROM CCUS

The stationary sources are distributed across the country with several clusters of power generation and industrial activity in key geographies: Appalachia (along the Ohio River), the Gulf Coast, Southern and Northern California, and the New Jersey seaboard (Figure 1-12). Many of these CO_2 sources are above, or adjacent to, viable CO_2 storage targets—labeled as saline formations on the map—making them prime candidates for CCUS retrofit.

The United States has abundant wind and solar resources, but their availability varies across the country. As shown in Figures 1-13 and 1-14, solar resources are concentrated in the southwest while wind capacity is primarily concentrated in the middle of the country. CO_2 storage resources also vary by region (Figure 1-15) and are well placed to enable decarbonization of nonrenewable energy in areas with limited solar and wind potential.

IX. CCUS CAN SUPPORT A LOW-CARBON ELECTRICITY SYSTEM

Power generation emits more CO_2 than any other sector around the world and in the United States; it represents the largest opportunity for the application of CCUS. CCUS can enable decarbonization of the power sector by supporting market share growth of variable output renewable energy sources and promoting greater U.S. energy independence and fuel diversity.

Wind and solar energy produce intermittent power—when the wind blows and the sun shines. However, power systems must provide electricity to the grid on demand. For areas without solar and wind capacity, and to increase the deployment and integration of renewables, it is necessary to have additional power sources that can be accessed quickly, reliably, at low cost, and, given increasing environmental concerns, with low-carbon emissions.

On average, in 2019, natural gas with CCUS is considered the lowest cost, high-capacity source

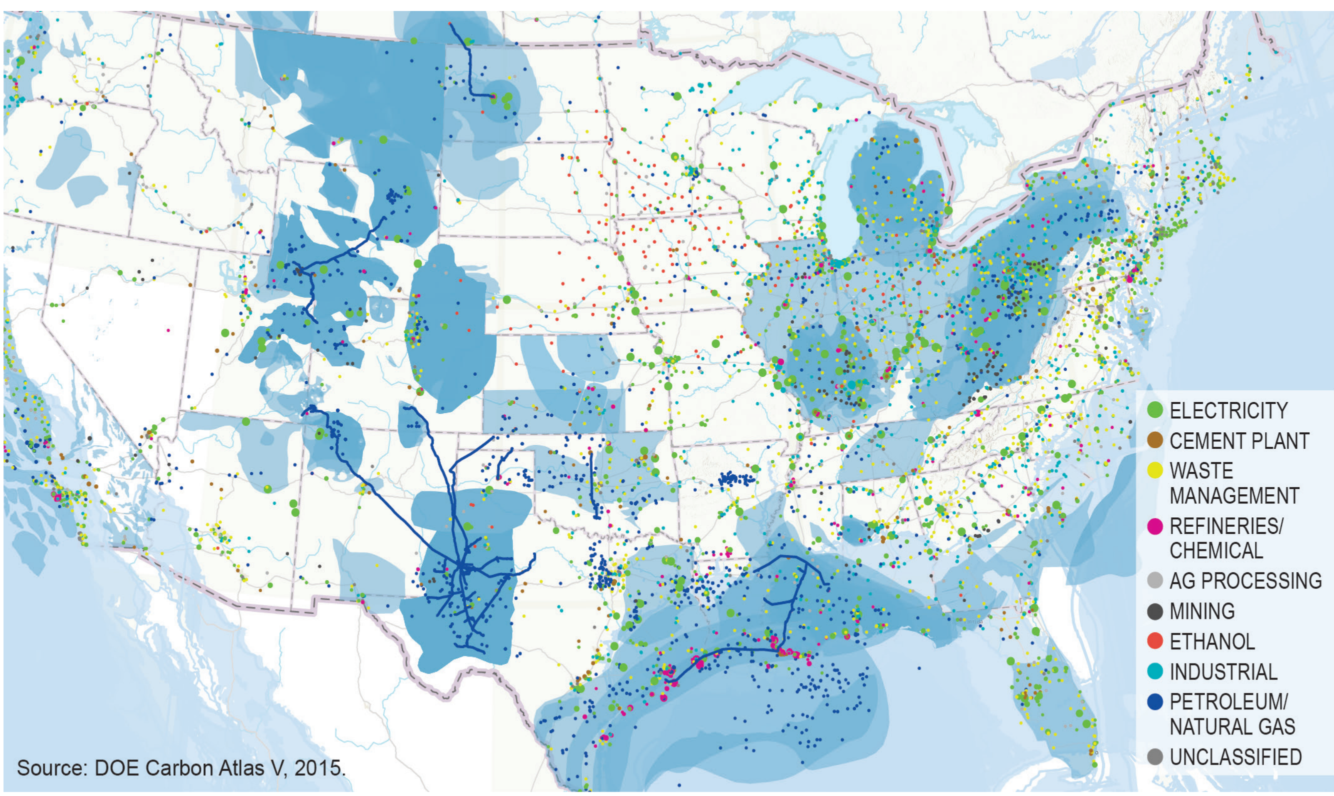
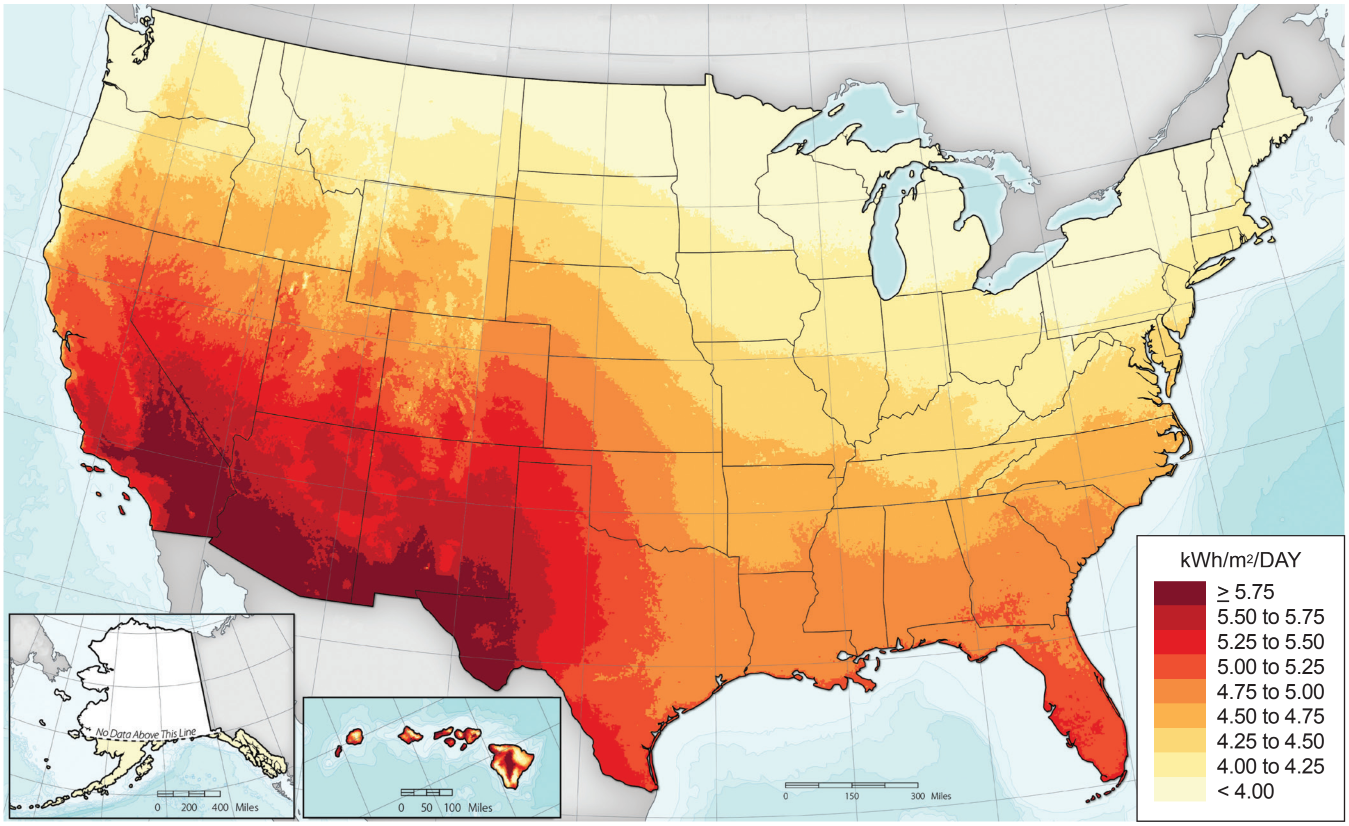
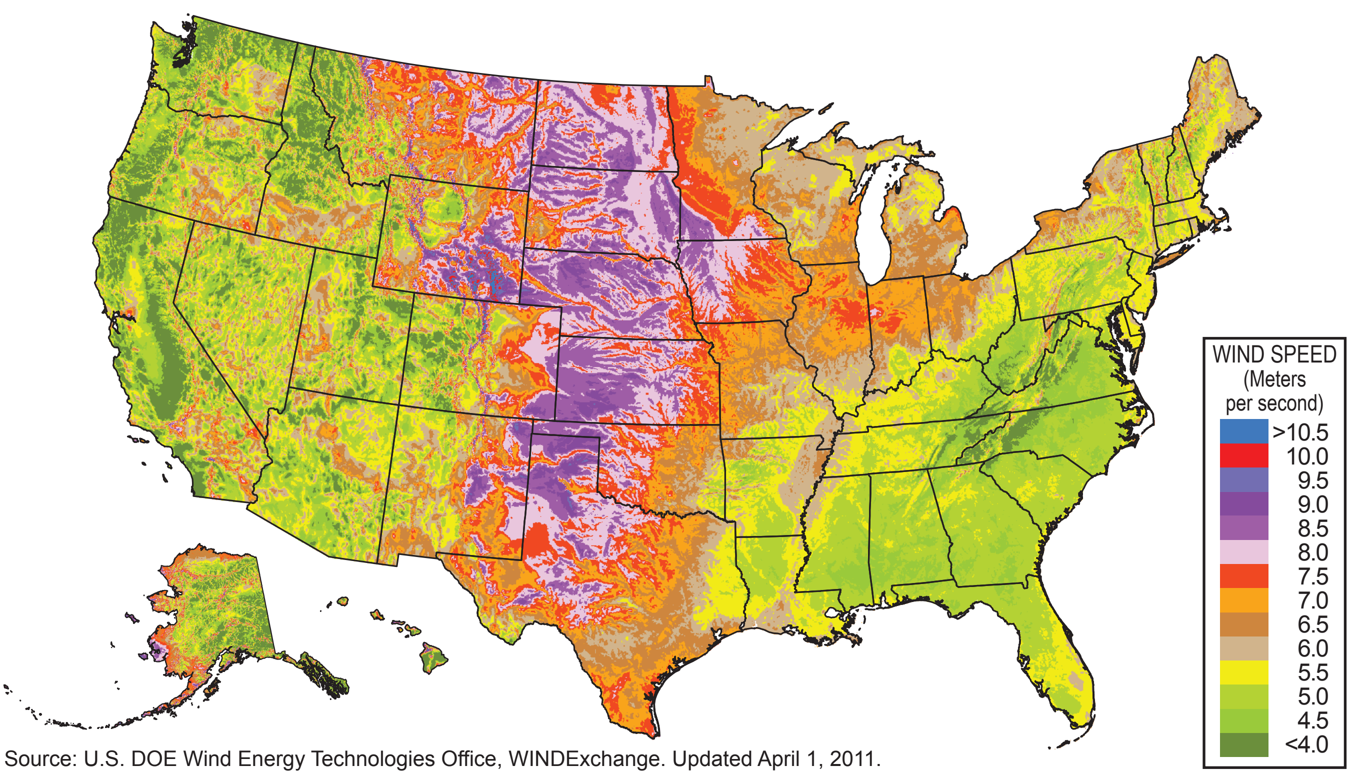


Figure 1-12. *U.S. Stationary Sources of CO_2 Emissions (by Type and Sized by Volume), Saline Formations, and Existing CO_2 Pipelines*



Source: National Renewable Energy Laboratory, Geospatial Data Science, Solar Maps.

Figure 1-13. *U.S. Average Daily Total Solar Resource, 1998-2016*



Source: U.S. DOE Wind Energy Technologies Office, WINDExchange. Updated April 1, 2011.

Figure 1-14. *U.S. Average Annual Wind Speed at 80 Meters*

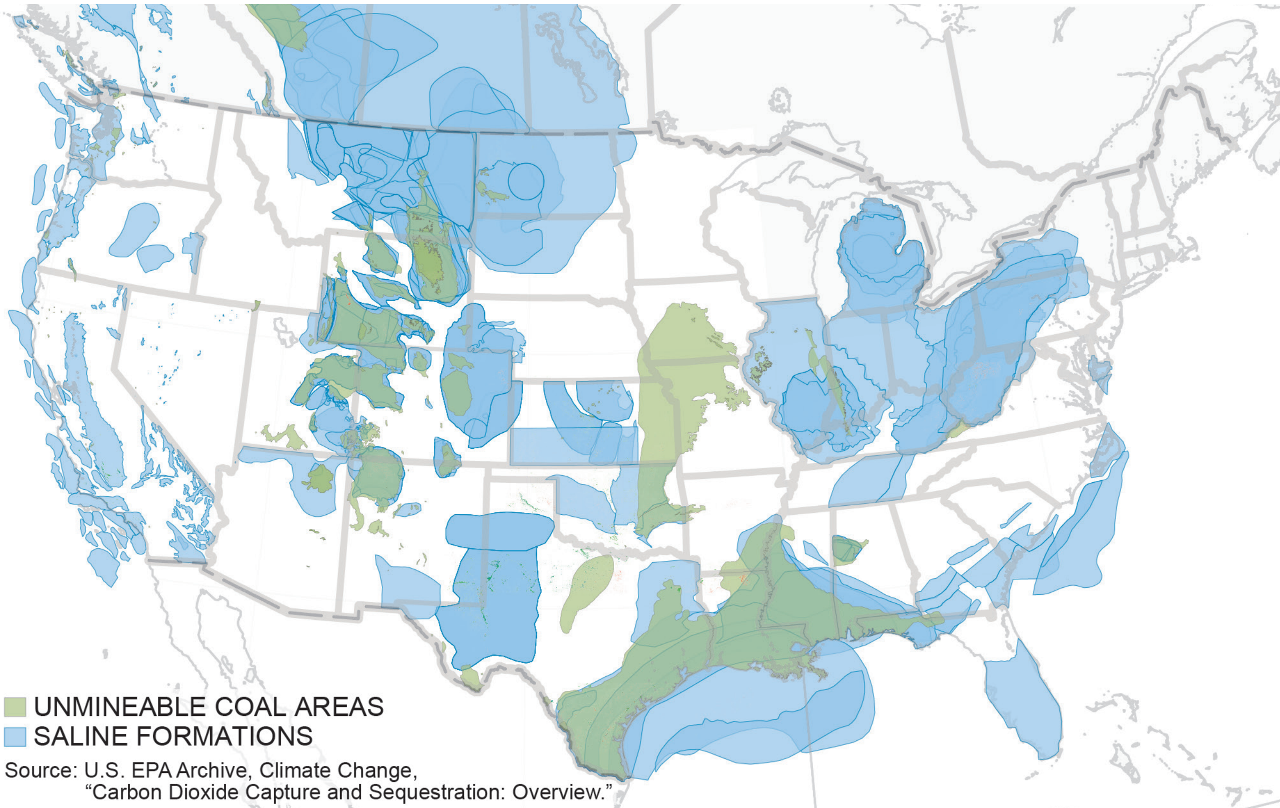


Figure 1-15. *U.S. Assessment of Geologic CO_2 Storage Potential*

of flexible low-carbon power in the United States. Advancements in battery storage have enabled short-term backup (up to four hours) of intermittent renewable energy. For extended periods (more than four hours) with no significant production of wind or solar power, natural gas with CCUS could be a cost-effective and low-CO_2 emission solution to maintain a reliable power supply.[32,33]

X. CCUS CAN ASSIST DECARBONIZATION OF HARD-TO-ABATE SECTORS

Economic sectors that are more costly or difficult to decarbonize are sometimes referred to as "hard to abate."[34] Such sectors include heavy industry—steel, cement, and chemical production—as well as heavy duty transportation such as trucking, shipping, and aviation. Hard-to-abate sectors represent 30% of total CO_2 emissions worldwide and are on the rise.[35]

Decarbonizing these sectors is difficult because of the special operational requirements for heavy industry, including high temperatures (500°C to 1,500°C) and high-capacity factors (24/7 operation). About 30% to 40% of emissions from a typical facility result from heat production, commonly from burning coal, gas, or petroleum coke. These unique requirements cannot currently be met by alternative technologies or fuel options.[36] Furthermore, 20% to 50% of emissions

32 International Energy Agency, IEA Greenhouse Gas R&D Programme, "Valuing Flexibility in CCS Power Plants," *IEAGHG Technical Report 2017-09,* December 2017, https://ieaghg.org/exco_docs/2017-09.pdf.

33 Boston, A., Bongers, G., and Byrom, S. (2018). "Renewables and the NEM: What are the limits and what else is needed to go zero?," Gamma Energy Technology, P/L, Brisbane Australia, https://anlecrd.com.au/wp-content/uploads/2019/02/Rpt-2-Final-web.pdf.

34 Powell-Tuck, R., *In Focus: Hard to Abate Sectors,* https://radar.sustainability.com/issue-20/in-focus-hard-to-abate-sectors/.

35 Energy Transitions Commission, *Mission Possible: Report Summary, November 2018,* p. 7, http://www.energy-transitions.org/sites/default/files/ETC_MissionPossible_ReportSummary_English.pdf.

36 International Energy Agency. (2019). "Transforming Industry through CCUS," IEA, Paris, https://www.iea.org/publications/reports/TransformingIndustrythroughCCUS/.

are byproducts of the fundamental industrial chemistry, which is represented by the grey bars in Figure 1-16.[37] An example of these byproducts is the release of CO_2 when limestone is heated to high temperatures to convert it to the key ingredient of cement.

CCUS is a key technology to mitigate the carbon intensity of heavy industry, especially for steel, cement, and chemicals production. The chemicals and petrochemicals sector represent the largest source of capturable CO_2 from industrial processes. CCUS can help decarbonize the production of hydrogen, ammonia, and methanol as well as high-value chemicals like ethylene, propylene, and aromatics. The role of CCUS in heavy industry is pivotal, and it grows over time as deeper emissions cuts are needed and other options are exhausted or uneconomic.[38]

37 Dell, R. (2018). "Steel Decarbonization in Context," Aspen Global Change Institute, https://www.agci.org/sites/default/files/pdfs/lib/main/Dell_11_12_1400_Dell_2018-11-12.pdf.

38 Dell, R. (2018); and Energy Transitions Commission. (2018). "Mission Possible: Reaching Net-Zero Carbon Emissions from Harder-to-Abate Sectors by Mid-Century," Report Summary, p. 18.

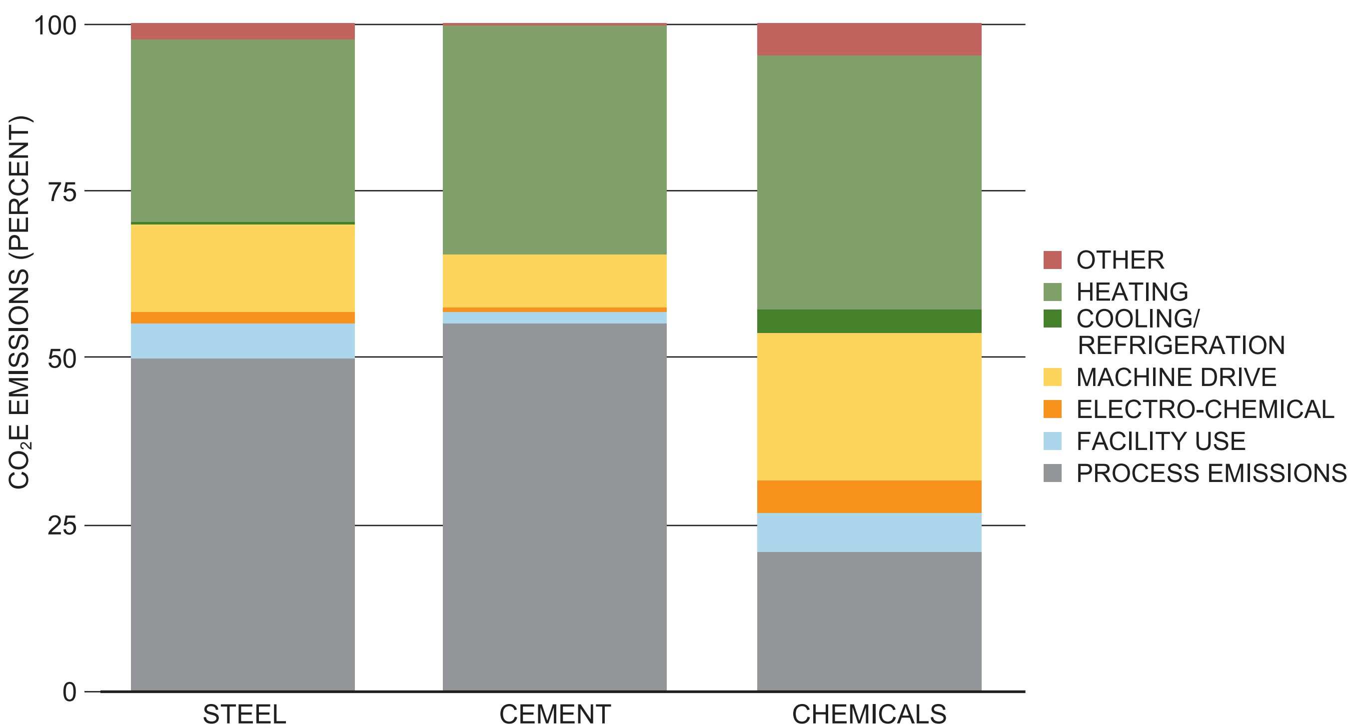
XI. CCUS CAN LEVERAGE EXISTING INFRASTRUCTURE

CCUS technologies can be retrofitted to reduce emissions from long-lived energy assets such as power plants, industrial boilers, and refineries.[39] Continued use of this existing infrastructure could preserve jobs and avoid costs when compared with the costs of premature retirement and replacement. Without CCUS retrofitted to these facilities, continued operation would significantly slow the reduction in CO_2 emissions.

XII. CONCLUSION

CCUS is an essential element in the portfolio of solutions needed to meet the dual challenge—delivering reliable energy while addressing the risks of climate change—at the lowest cost over the long term. Governments around the world are already making policy decisions

39 International Energy Agency. (2019). "Transforming Industry through CCUS," IEA, Paris, https://www.iea.org/publications/reports/TransformingIndustrythroughCCUS/.



Source: Dell, R. (2018). "Steel Decarbonization in Context," Aspen Global Change Institute.

Figure 1-16. *CO_2 Equivalent Emissions Associated with the Production of Steel, Cement, and Chemicals* to reduce CO_2 emissions, and the United States is positioned to lead implementation because of its unique combination of technical expertise, CCUS experience, and geologic capacity to store CO_2. By using a combination of technologies to decrease the amount of CO_2 emissions from stationary sources, CCUS deployment can help advance progress on climate targets by removing CO_2 from the energy system, as well as removing CO_2 from carbon-intensive processes, and supporting increased use of lower-carbon energy sources. To remain a leader in CCUS, and to realize the potential economic and environmental benefits from its deployment, the United States will need continued investment in technology and a durable regulatory and legal framework that provides the clarity and certainty to create markets and encourage private investment.

Chapter 2 of this report, "CCUS Supply Chains and Economics," describes the CCUS supply chains, associated costs, and enablers for future projects. It also details the United States' leadership in CCUS and explains the factors that uniquely position the U.S. for continued leadership in emerging CCUS markets.

Chapter 3, "Policy, Regulatory, and Legal Enablers," outlines the CCUS policy, regulatory, and legal landscape and provides detailed recommendations to enable deployment. To achieve at-scale deployment, CCUS must overcome substantial hurdles to financing and regulatory clarity and certainty. A durable policy and legal framework can provide the clarity and certainty needed to create markets and encourage private investment.

Chapter 4, "Building Stakeholder Confidence," underscores the critical role that stakeholders play in enabling at-scale deployment of CCUS, and offers a set of recommended actions designed to effectively engage all stakeholders and build confidence. At present, awareness of CCUS among the general public is low; accordingly, the impact CCUS technologies can play to cost-effectively reduce CO_2 is not well-understood. Building the commitment needed to achieve at-scale deployment will require education, transparency and trust.