STRENGTHENING INTERNATIONAL COLLABORATION ON CARBON CAPTURE USE AND STORAGE

C2ES CENTER FOR CLIMATE AND ENERGY SOLUTIONS

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Carbon capture use and storage (CCUS) technologies are critical to achieving global and national climate and energy goals[1] In recent decades, industry and governments have achieved significant milestones in advancing CCUS technologies. There are now 18 large-scale CCUS facilities operating around the world and, to date, 220 million tonnes of anthropogenic CO_2 have been safely stored below ground.[2] However, the pace of development and deployment must rapidly accelerate if CCUS is to achieve its potential role in reducing greenhouse gas emissions while ensuring sustainable development.

Experience demonstrates that two critical factors in advancing CCUS technologies are adequate policy drivers and incentives and the availability of finance. Although the relevant decision-making rests primarily with national governments and the private sector, international collaboration can help to strengthen both of these critical factors. The 2019 G20 summit in Osaka and the energy and environment ministerial meeting in Karuizawa, Japan, present important opportunities to strengthen international collaboration on CCUS by building on existing initiatives and focusing on future efforts.

Toward that end, this paper reviews projected global, regional, and sectoral CCUS needs; policy examples and options at the national level; financing challenges and opportunities; and identifies a range of options for strengthening international collaboration on CCUS at the G20 meetings in Japan.

PROJECTED GLOBAL NEEDS FOR CCUS IN A LOW-CARBON FUTURE

The Paris Agreement aims to limit the increase in average global temperature to "well below two degrees Celsius above pre-industrial levels" and encourages "efforts to limit the temperature increase to 1.5 degrees Celsius above pre-industrial levels."[3] The agreement also aims for "a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases" in the second half of the 21st century.[4] The Intergovernmental Panel on Climate Change Fifth Assessment Report noted that more than half of their models could not limit climate change to two degrees Celsius without CCS; those that could saw costs rise 138 percent.[5] Ten nations included CCUS technologies in their Nationally Determined Contributions (NDCs), including China, Saudi Arabia, and the United States. A major challenge is that even if all of the signatories to the Paris Agreement achieved their NDCs, the emissions reductions would not be sufficient to limit global warming to two degrees Celsius; rather, they would limit it to roughly 2.7 degrees Celsius.[6] An increase in ambition will be necessary to achieve net zero emissions in the second half of this century.

The International Energy Agency (IEA) conducts scenario assessments to help inform its over 30 partner nations on the outlook for energy use and emissions. The Two Degree Scenario (2DS) outlines a pathway to achieving the goals of the Paris Agreement. The Beyond Two Degree Scenario (B2DS) reflects the aspirational goals of the Paris Agreement. In the 2DS, CCS technologies provide 14 percent of the emissions reductions needed by 2060 (See Figure 1). Furthermore, to move from 2DS to the B2DS, 32 percent of the additional emissions reductions would come from CCS (See Figure 2).[7] For example, in 2060, almost 100 Gt of additional

CO_2 would be captured under the B2DS compared to the 2DS and a large part of this additional captured CO_2 would be from the industrial sector.[8] In both the 2DS and the B2DS, in 2060, roughly 40 percent of captured CO_2 is from Bio-energy with CCS (BECCS).[9] Indeed, the IPCC's Special Report on Global Warming of 1.5 Degrees reflects an increasing focus on BECCS and direct air capture, rather than on CCUS technologies on fossil fuels.[10]

In 2017, the IEA introduced the Sustainable Development Scenario (SDS), which is consistent with the Paris Agreement, but also prioritizes universal energy access in line with the U.N. 2030 Agenda for Sustainable Development.[11] In the SDS, more than 80 percent of CCS technology is deployed in the United States and China, coal-fired power generation without CCS is phased-out, and emissions are reduced by an additional 9 percent by 2040 compared to a scenario implementing existing and announced policies.[12] This analysis shows how critical CCS is to the U.N. Sustainable Development Goals of universal energy access.

Figure 1: CCS in the Two-Degree Scenario

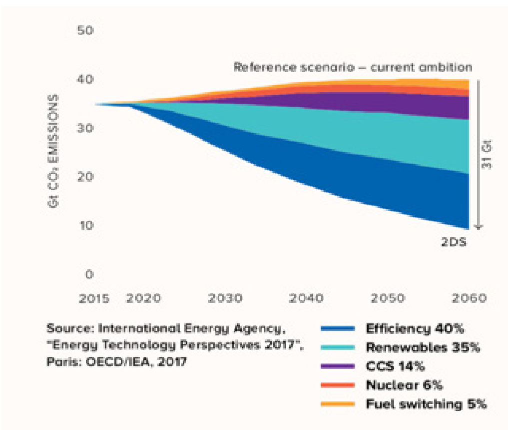


Figure 2: CCS in the Beyond-Two-Degree Scenario

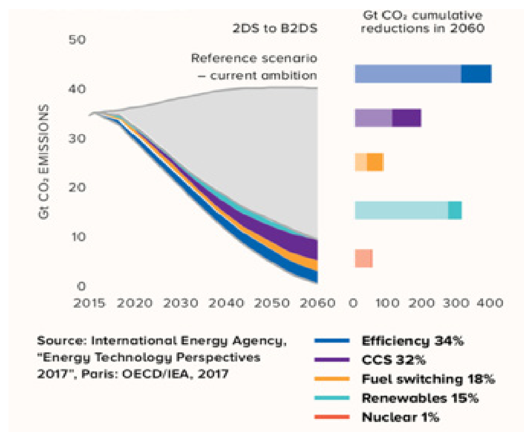


Figure 3: CCS by Sectors and Regions in the Two-Degree Scenario

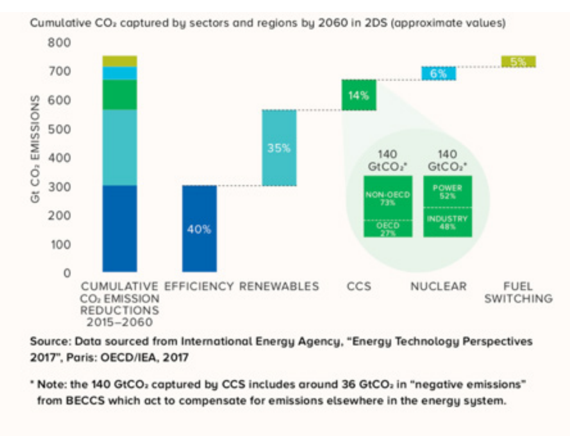
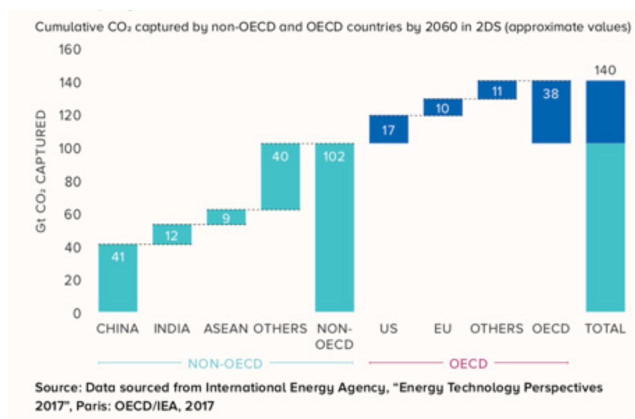


Figure 4: CCS Deployment in Non-OECD and OECD Countries in the Two-Degree Scenario



Source: Global CCS Institute, The Global Status of CCS: 2017, 20-21 (Australia: GCCSI, 2017).

Table 1: Regional Potential for CCUS Deployment

REGION	EMISSIONS CHALLENGES	CO_2 UTILIZATION AND STORAGE OPPORTUNITIES	LEGAL AND POLICY FRAMEWORK READINESS
Asia	• Increased use of coal-fired power generation is expected. • There are growing industrial sector emissions.	• Many onshore storage sites have been identified. • There is potential for offshore storage. • Further storage site identification and characterization is needed.	• Framework needs to be developed. • There are institutional capacity constraints.
North America	• Emissions solutions for natural gas-fired power generation and industrial sector emissions are needed.	• There is potential for CO_2-EOR. • Many onshore storage sites have been identified and characterized. • There is potential for offshore storage (e.g. US and Mexico). • Potential for non-EOR CO_2U (e.g., from the NRG COSIA Carbon XPRIZE).	• CO_2-EOR framework is better developed than for saline storage. • Ownership and liability for saline storage of CO_2 is not settled in all U.S. states. In Alberta, the Crown owns the pore space.
Europe & Eurasia	• Emissions solutions for natural gas-fired power generation and industrial sector emissions are needed	• There is potential for onshore and offshore storage. • Further storage site identification and characterization is needed.	• Framework for storage needs to be developed. • There are institutional capacity constraints in non-OECD Europe and Eurasia
Africa	• Increased use of coal-fired power generation is expected. • There are growing industrial sector emissions	• Very little storage site identification and characterization has taken place.	• Framework needs to be developed. • There are institutional capacity constraints.
Central & South America	• Emissions solutions for coal- and natural gas-fired power generation and industrial sector emissions are needed.	• There is potential for CO_2-EOR and offshore storage. • Very little storage site identification and characterization has taken place.	• Framework needs to be developed. • There are institutional capacity constraints.
Middle East	• Emissions solutions for natural gas-fired power generation and industrial sector emissions are needed.	• There is potential for CO_2-EOR. • Further storage site identification and characterization is needed.	• Framework needs to be developed. • There are institutional capacity constraints.

SECTOR- AND GEOGRAPHY-BASED ASSESSMENT OF CCUS POTENTIAL

In 2015, the largest sources of global CO_2 emissions were, in order: electricity and heat (42 percent), transportation (24 percent), industry (19 percent), residential (6 percent), services (3 percent), and other (such as agriculture, forestry, and fishing)(7 percent).[13] Looking ahead, projected emissions are expected to continue to grow. Global energy demand could rise by 30 percent by 2040, driven by economic growth, an expanding population, and increased urbanization.[14] Fossil fuels are expected to meet most of the world's energy demands through 2040.[15] Therefore, a sector-based assessment of CCUS needs reveals that the power sector is a leading candidate for CCUS deployment.

In addition to the power sector, however, CCUS technologies will also be essential to decarbonize the industrial sector, including steel, cement, and fertilizer production, natural gas processing, and refining. The industrial sector's emissions arise from its combustion of fossil fuels for energy, but also its direct emissions from the transformation of raw materials both physically and chemically. For many of these production and processing operations, there is no practical alternative to CCUS to achieve deep decarbonization because CO_2 is a process emission. For example, the cement industry generates roughly 5 percent of the world's GHG emissions.[16] Over half of the CO_2 emissions from cement production are from calcination and the rest is mostly from fuel combustion to provide thermal energy for calcination; only about five percent of the CO_2 emissions from cement production are from the use of electricity (although it can range from between one to 10 percent).[17] The steel and iron industry also generates about five percent of the world's CO_2 emissions.[18] Many of these industries are likely to grow in major developing economies as urbanization and infrastructure development increases demand for steel and cement.[19] The production of plastics, mostly from fossil fuels, is expected to generate 15 percent of the world's annual carbon emissions by 2050.[20] The largest sources of industrial emissions in the world are China, India, the European Union and the United States and more detailed information about the industrial emissions of these countries is provided below.

In the IEA 2DS, by 2060, CCS will provide a global total of 140 $GtCO_2$ of emissions reductions, 52 percent from power sector CCS deployment and 48 percent from industrial sector CCS deployment (see Figure 3). Seventy-three percent of CCS deployment will be in non-OECD (Organization for Economic Co-operation and Development) nations and 27 percent will be in OECD nations. Breaking this down further, an estimated 41 $GtCO_2$ of emissions reductions will come from China, 12 $GtCO_2$ from India, 9 $GtCO_2$ from other ASEAN (Association of Southeast Asian Nations) nations, and 40 $GtCO_2$ from other developing nations (see Figure 4). Among OECD nations, 17 $GtCO_2$ of emissions reductions will come from the United States, 10 $GtCO_2$ from the European Union, and 11 $GtCO_2$ from other developed nations.

The deployment of CCUS technologies in both the power and industrial sectors is supported by the multiple benefits provided by these technologies: carbon emissions reduction that mitigates climate change, the opportunity to increase economic growth, and, in many nations, energy security benefits. For example, since many nations, like China, India, and the United States have large coal reserves, policymakers are often interested in finding ways to develop domestic natural resources and CCUS offers a low-carbon pathway for that goal.

Many of the opportunities and challenges related to CCUS deployment vary on a regional basis, so it is helpful to consider these regions on the basis of their emissions profile, re-use and storage opportunities for captured carbon, and the readiness of their legal and regulatory frameworks. Table 1 reviews these factors.

All of the G20 nations have some opportunity for deployment of CCUS technologies. In the G20 as a whole, in 2015, CO_2 emissions from coal combustion were more than 82 percent higher than 1990 levels and CO_2 emissions from natural gas combustion were more than 59 percent higher.[21] In 2015, the top ten nations in terms of CO_2 emissions were, in order: China, the United States, India, the Russian Federation, Japan, Germany, Korea, the Islamic Republic of Iran, Canada, and Saudi Arabia.[22] The two largest sources, China and the United States, emitted 28 percent and 15 percent respectively of all global emissions.[23] =

ASIA

CCUS technologies will be needed in Asia because the region is expected to continue to use coal-fired power generation for decades and demand for coal and gas is expected to continue to grow through 2040.[24] Industrial sector emissions are likely to grow as urbanization trends continue and infrastructure using steel and cement continues to be built. This region is also increasing its manufacturing capacity as global companies shift their operations to areas with lower labor costs. There may be opportunities for both onshore and offshore storage in the region, but much more work needs to be done on storage site identification and characterization and on building the legal and regulatory frameworks to enable large-scale CCUS deployment. In many developing nations in Asia, there are institutional capacity constraints and it may be difficult to ensure that requirements related to measurement, monitoring, and verification of storage sites are enforced.

China is among the nations that are best suited for CCUS deployment. In 2015, China's CO_2 emissions from the combustion of coal were more than 310 percent higher than 1990 levels and its CO_2 emissions from the combustion of natural gas were significant as well.[25] About one-third of China's installed coal-fired generation capacity, which is nearly half of the entire world's coal-fired generation capacity, is suitable for retrofit with CCUS technology.[26] China's demand for coal is expected to decrease through 2040 and its demand for natural gas is expected to increase.[27] China also produces almost two-thirds of the world's cement and almost half of the world's steel; it is the world's largest producer of both.[28] Growing urbanization in China is a primary driver of the production of steel, cement, and aluminum in the country.[29] Recent analysis projects that China's cement production could rise from 1,882 million tons in 2010 to a peak of 2,229 million tons in 2020 before slowing down to 1,647 million tons in 2050.[30] China's Paris pledge includes the peaking of CO_2 emissions by 2030, so a lot of progress on CCUS development is required, including relating to CO_2 storage. There are at least 20 CCUS projects in some stage of development in China.[31] According to publicly available storage resource assessments, China has identified sites to store 2,400 gigatonnes of CO_2, but these storage formations need to be better characterized.[32]

In **India**, almost 300 million people lack access to electricity, so the country is facing the dual challenges of expanding energy access while also reducing carbon emissions.[33] In 2015, India's CO_2 emissions from the combustion of coal were more than 308 percent higher than 1990 levels and most of its coal-fired power generation was installed in the last fifteen years.[34] Similarly, in 2015, India's emissions of CO_2 from the combustion of natural gas were more than 300 percent higher than 1990 levels.[35] India's national energy plan for 2017-2020 anticipates developing more coal reserves to nearly double coal production.[36] India's demand for both coal and natural gas are expected to increase through 2040.[37] While the Indian government has not expressed an interest in limiting the total installed capacity of coal-fired power generation, at a climate summit in August 2017, Indian Minister of State for Power and Renewable Energy Piyush Goyal expressed an openness to investing in CCUS technologies.[38] CCUS technologies could also be helpful to the Indian industrial sector. Between 2005-2013, India's industrial emissions grew almost 9 percent each year, a higher rate of growth than the country's total GHG emissions, which was less than 6 percent each year.[39] Over that time period, the industrial sector represented almost 20 percent of India's GHG emissions; most of these emissions are from coal consumption in the industrial sector.[40] Looking ahead, India plans to increase industrial production, especially of steel, under the Make in India Initiative, while it also aims to achieve its Paris pledge of lowering the GHG emissions intensity of the country's Gross Domestic Product by 33 to 35 percent from 2005 levels by 2030.[41] India has identified sites to store 50 gigatonnes of CO_2, but much work remains to be done to identify and characterize potential CO_2 storage sites in the country.

Australia also has long-term interests in CCUS technologies. Australia produces more than two-thirds of its electricity and heat using coal, but its use of natural gas continues to grow.[42] In 2015, while CO_2 emissions from coal combustion were only 22.7 percent higher than 1990 levels, its CO_2 emissions from natural gas combustion were 131 percent higher.[43] There are three CCUS projects in the construction and development stages in Australia, including the Gorgon project, in which CO_2 emissions from the Liquified Natural Gas (LNG) facility will be stored onshore on Barrow Island.[44] According to publicly available storage resource assessments, Australia has identified sites to store 400 gigatonnes of CO_2, though more work could be done to characterize the storage formations.[45]

Japan is increasing its investment in CCUS technologies. In 2015, Japan's CO_2 emissions from coal increased by 53.8 percent over 1990 levels, while CO_2 emissions from natural gas combustion increased by 113 percent.[46] Japan's demand for coal is expected to decrease steadily through 2040, while its demand for natural gas is expected to decrease and then increase moderately by 2040, without returning to 2015 levels.[47] In Japan, there is one large pilot CCUS project that is operational, the Tomakomai CCS Demonstration Project. More than 100,000 tonnes of CO_2 captured from the refinery's hydrogen production is being injected offshore each year for three years.[48] According to publicly available storage resource assessments, Japan has identified sites to store 140 gigatonnes of CO_2 based on a desktop analysis; more work to characterize these storage formations could be undertaken.[49]

Indonesia has seen some of the most dramatic increases in emissions from coal combustion. In 2015, Indonesia's CO_2 emissions from coal combustion increased by 806.6 percent over 1990 levels, reaching an absolute level of 164.9 million tonnes of CO_2, and Indonesia's CO_2 emissions from natural gas combustion increased by 219.9 percent, reaching an absolute level of 77.8 million tonnes of CO_2.[50] Much work remains to be done to identify and characterize potential CO_2 storage sites in the country. The Gundih CCS pilot is an example of the type of demonstration project that could be useful. CO_2 emissions separated from gas produced at the Gundih gas field will be injected in subsurface sandstone after the completion of geologic studies, the establishment of a regulatory framework, and public engagement.[51]

Korea has also seen an increase in emissions from coal combustion. In 2015, Korea's CO_2 emissions from coal combustion were 247.5 percent higher than 1990 levels.[52] Like Indonesia, much work remains to be done to identify and characterize potential CO_2 storage sites in Korea.

NORTH AMERICA

North America has been a leading region for CCUS technologies, especially CO_2 enhanced oil recovery (CO_2-EOR), which was commercialized in this region almost fifty years ago. North America has also been the site of pioneering saline storage projects in Canada and the United States, such as the Shell Quest project involving hydrogen production associated with oil sands operations and the Archer Daniels Midland project at an ethanol facility. In the North American region, emissions solutions for natural gas-fired power generation and industrial sector emissions will be needed because demand for natural gas is expected to increase while demand for coal is expected to continue to decrease through 2040.[53] In many parts of the region, there has been robust identification and characterization of potential storage sites, but this is not uniform across all three countries. Further work could also be done to identify and characterize sites for offshore storage. Given the region's history with CO_2-EOR, the legal and regulatory framework is well-developed in parts of the United States and Canada. Issues related to ownership and liability for CO_2 stored in saline formations, however, are not settled in all U.S. states.

In the **United States**, most of the coal-fired power generation was installed before 1990, so the economics of CCUS retrofits are challenging.[54] American CO_2 emissions from coal combustion have declined by more than 20 percent from 1990 levels and CO_2 emissions from natural gas combustion have increased by more than 45 percent.[55] Looking ahead, demand for coal is expected to decline in the United States and demand for natural gas is expected to increase through 2040.[56] CCUS technologies are also important for the industrial sector, which was responsible for 27 percent of the country's CO_2 emissions from fossil fuel combustion in 2016, including both direct emissions and from its use of electricity.[57] Industrial sector emissions in the United States declined between 1990 and 2016 by 14 percent, due to efficiency improvements, fuel switching, and a structural shift in the U.S. economy towards services rather than manufacturing.[58] However, certain sub-industries, such as chemicals, food products, metal products, plastics, aluminum, and transportation equipment, are expected to grow and by 2050, the overall industrial sector's CO_2 emissions are expected to increase.[59] There are 15 CCUS projects in operation in the United States, including the world's first commercial-scale deployment of CCUS technology at an ethanol plant in Illinois. Several more may be in development after the extension and expansion of the Section 45Q tax credit. According to publicly available storage resource assessments, the United States has identified sites to store 8,150 gigatonnes of CO_2 and these storage formations are well-characterized.[60]

Canada has also been a leader in CCUS technologies. Canada has seen CO_2 emissions from coal combustion drop by more than 22 percent from 1990 levels, while its CO_2 emissions from natural gas combustion have increased by more than 78 percent.[61] In 2016, 81% of Canada's electricity generation was from non-emitting sources, with coal comprising 9% of national electricity generation but representing about half in the provincial generation mix of three provinces – Saskatchewan, Alberta, and Nova Scotia.[62] Canada's domestic policy regarding coal-fired power requires the phasing out of traditional (or unabated) coal – meaning that any coal use for electricity generation beyond 2030 would require CCUS to operate. The first commercial-scale coal-fired power plant retrofitted with CCUS technology was the SaskPower Boundary Dam project. In addition, there are two other large-scale CCUS projects in operation in oil and gas applications in Canada (e.g. Shell Quest and the Weyburn-Midale CO_2-EOR project) and another under construction (e.g. the Alberta Carbon Trunk Line). According to publicly available storage resource assessments, Canada has identified sites to store 400 gigatonnes of CO_2, and these storage formations are well-characterized.[63]

Mexico is a growing area of focus for CCUS deployment. It has experienced a significant growth in coal and natural gas emissions. In 2015, Mexico's CO_2 emissions from coal combustion were more than 263 percent higher than 1990 levels and Mexico's CO_2 emissions from natural gas combustion were more than 198 percent higher.[64] According to publicly available storage resource assessments, Mexico has identified sites to store 100 gigatonnes of CO_2, though more work could be done to characterize the storage formations.[65]

EUROPE AND EURASIA

In Europe and Eurasia, emissions solutions for coal- and natural gas-fired power generation and industrial sector emissions are needed. The European Union has seen emissions from coal combustion increase by more than 41 percent from 1990 levels, while emissions from natural gas rose by almost 25 percent.[66] Non-OECD Europe and Eurasia together have seen coal emissions decline by more than 48 percent from 1990 levels and natural gas emissions decline by more than 18 percent.[67] In the European Union, demand for natural gas is expected to experience both increases and decreases ending slightly below 2016 levels by 2040 while demand for coal is expected to decrease steadily through 2040.[68] By contrast, in Eurasia, demand for natural gas is expected to increase steadily while demand for coal is expected to experience increases and decreases ending slightly above 2016 levels by 2040.[69] In addition, the industrial sector is responsible for one-fifth of European Union emissions and emissions from this sector are expected to increase.[70] Currently, Europe's industrial emissions (857 $MtCO_2$) are already larger than emissions from all of its coal-fired power plants (775 $MtCO_2$).[71] Europe is the world's second largest steel producer, following China.[72] Roughly half of European steel involves recycling of scrap, but increasing demand ensures that new production will continue.[73] Some European nations, like Germany and the United Kingdom, have large chemical industries, which create many products, including ethylene for use in polymers and plastics.[74]

Some European nations have invested more in CCUS technologies than others and in some countries, the switch to gas from coal has been more significant. There is potential for both onshore and offshore storage, but further storage site identification and characterization is needed. In many European and Eurasian nations, the legal and regulatory framework for CO_2 storage needs to be developed. In non-OECD Europe and Eurasia, there may be institutional capacity constraints.

The **United Kingdom** is among the European countries that are more interested in CCUS technology; the current government's Clean Growth Strategy prioritizes international leadership in CCUS, including investing up to 100 million pounds in innovation to reduce costs.[75] In the United Kingdom, CO_2 emissions from coal combustion were almost 64 percent lower than 1990 levels and CO_2 emissions from natural gas combustion were more than 36 percent higher.[76] Analysis suggests that CCUS could reduce industrial CO_2 emissions in the United Kingdom by 37 percent.[77] According to publicly available storage resource assessments, the United Kingdom has identified sites to store 80 gigatonnes of CO_2, and these storage formations are well-characterized.[78]

Norway has also been a leader in CCUS technology development. Norway's CO_2 emissions decreased by more than 17 percent from 1990 levels while CO_2 emissions from natural gas combustion were more than

141 percent higher.[79] Analysis conducted by industrial companies suggests that using CCS could achieve 36 percent of the industrial sector's needed emissions reductions.[80] There are two operational CCUS projects in Norway: the Sleipner project has been capturing CO_2 from gas development for offshore storage for over 20 years and the Snohvit project has been capturing CO_2 from LNG production for offshore storage for over 10 years. There are also multiple additional CCUS projects in development. According to publicly available storage resource assessments, Norway has identified sites to store 70 gigatonnes of CO_2 and these storage formations are well-characterized.[81]

AFRICA

In Africa, continued use of coal-fired power generation is expected as demand for both coal and natural gas is expected to increase through 2040.[82] There are also growing industrial sector emissions as urbanization trends continue and steel and cement are produced to build more infrastructure. To date, very little CO_2 storage site identification and characterization has taken place and the legal and regulatory framework for CO_2 storage needs to be developed. In many developing nations in Africa, there are institutional capacity constraints and it may be difficult to ensure that requirements related to measurement, monitoring, and verification of storage sites are enforced. **South Africa** is a good candidate for CCUS technology deployment because it produces more than two-thirds of its electricity and heat using coal.[83] In 2015, South Africa's CO_2 emissions from coal combustion were more than 75 percent higher than 1990 levels.[84] South Africa's demand for coal is expected to decrease and its demand for natural gas is expected to increase through 2040.[85] According to publicly available storage resource assessments, South Africa has identified sites to store 150 gigatonnes of CO_2, though more work could be done to characterize the storage formations.[86]

CENTRAL AND SOUTH AMERICA

In Central and South America, emissions solutions for both coal and natural gas-fired power generation are needed because demand for both coal and natural gas is expected to increase through 2040.[87] Solutions for industrial sector emissions will be needed as urbanization trends continue and emissions from steel and cement production increase as more infrastructure is built. There is potential for both onshore and offshore CO_2 storage although very little storage site identification and characterization has taken place. The legal and regulatory framework needs to be developed. In many developing nations in Central and South America, there are institutional capacity constraints and it may be difficult to ensure that requirements related to measurement, monitoring, and verification of storage sites are enforced. **Brazil** is one of the leading South American nations in CCUS technology development. In 2015, Brazil's CO_2 emissions from coal combustion had increased by more than 145 percent over 1990 levels.[88] Brazil's demand for coal is not expected to increase but its demand for natural gas is expected to increase through 2040.[89] There is one CCUS project in operation in Brazil, the Petrobras Santos Basin Pre-Salt oil field which captures CO_2 from natural gas processing for offshore CO_2-EOR. According to publicly available storage resource assessments, Brazil has identified sites to store 2,000 gigatonnes of CO_2, though more work could be done to characterize the storage formations.[90]

THE MIDDLE EAST

In the Middle East, there are growing emissions from natural-gas fired power generation and from the industrial sector. In 2015, S**audi Arabia's** CO_2 emissions from natural gas combustion were 156.3 million tonnes, a 261.9 percent increase over 1990 levels.[91] Demand for coal is expected to remain low while demand for natural gas is expected to increase through 2040.[92] There are two operational CCUS projects in Saudi Arabia. In the **United Arab Emirates**, the Al Reyadah project became the world's first commercial-scale steel plant to deploy CCUS technology. There is potential for CO_2-EOR in this region, but much work remains to be done to identify and characterize potential CO_2 storage sites. The legal and regulatory framework needs to be developed. Like many developing regions, in many countries in the Middle East there are institutional capacity constraints.

POLICY: STATUS AND OPTIONS

Given the high upfront costs of CCUS deployment – and the fact that carbon emissions remain largely an externality in most economies – strong policy support will be essential to mobilize the scale of finance needed to achieve wide-scale deployment consistent with meeting global climate goals. A number of national and subnational governments have begun putting in place a range of policies to facilitate and to incentivize CCUS deployment. These early experiences provide examples and lessons as other countries develop the necessary policy frameworks. Policies that can help to scale up CCUS deployment include:

- Carbon pricing;
- Support for research, development, demonstration and deployment (RDD&D);
- Financial incentives for deployment;
- Clean energy standards; and
- Enabling legal and regulatory frameworks to manage ownership and storage of captured CO_2.

Nations can learn from each other at a high level in the policy arena. For example, they can identify research priorities for public funding, they can identify categories of CCUS projects that are near commercialization but need a lower cost of capital, they could determine which types of financial institutions are likely to become active participants and partners, and they could identify certain project risks that are likely to need public sector backing. At the same time, the details of specific CCUS policies may be harder to translate across unique political and economic histories and contexts. In developing and implementing CCUS policies, it is important to communicate around the value of CCUS as a climate solution.

National and subnational governments have a role to play in changing the narrative around CCUS, so that it is more widely understood as an essential component of the global response to climate change. One example of the type of messaging that would be helpful is the U.S. Mid-Century Strategy, which underscores the importance of Bioenergy with CCS (BECCS) technologies to drive down net GHG emissions.[93] Including CCUS technologies in national strategy documents helps demonstrate a commitment to seeing the technologies develop through commercialization, which is a useful market signal for investors. It also helps the public understand that CCUS technologies are part of a portfolio of strategies to address climate change.

Countries also can draw lessons from policies that succeeded in accelerating the deployment of renewable energy generation, like wind, solar, and geothermal energy. These clean energy technologies have achieved significant growth in deployment over the last couple of decades supported by customized policies in different nations. As a result, it is possible to learn from these experiences and to tailor policies to achieve a similar scale-up of CCUS technologies. The need for policy parity is a key theme that emerges from the literature on CCUS technology deployment.

CARBON PRICING

Pricing carbon could be an effective means of encouraging investment in CCUS projects. Carbon pricing policies may take several forms, including both sector-specific and economy-wide cap-and-trade programs as well as carbon taxes (or "carbon fees") that may or may not include a rebate component for consumers. Economists support carbon pricing policies because they are cost-effective and market-based solutions.

In Norway, the establishment of a carbon tax in 1991 motivated the development of offshore CO_2 storage projects. The Sleipner CCS project in the North Sea began operations in 1996 and captures CO_2 from gas processing. It was the first project in the world to be developed for the purpose of storing manmade CO_2 to mitigate climate change. The Snohvit CCS project in the Barents Sea began operations in 2008 and captures CO_2 from LNG processing.

Norway's carbon tax model could be a good model for some countries. In other countries, given the political infeasibility of implementing carbon pricing, it is worth considering other alternatives in the near-term.

SUPPORT FOR RESEARCH, DEVELOPMENT, DEMONSTRATION AND DEPLOYMENT (RDD&D)

It is important to emphasize that some CCUS technologies are already technically proven and ready for deployment at an accelerated pace. Therefore, support for RDD&D can range from a focus on deployment support for such technologies as well as a focus on early stage research on next-generation CCUS technologies. Commercialization support for CCUS projects can be quite expensive; a single project can cost as much as $1 billion. Certainly, first-of-a-kind projects are usually more expensive than next-of-a-kind projects. In Canada, after the retrofit with CCUS technology of the Boundary

Dam project, experts estimated that they would be able to reduce total project costs on any similar facility by thirty percent.[94] More recently, the International CCS Knowledge Centre's feasibility study to retrofit the nearby Shand power plant with CCUS suggests a potential for even deeper cost reductions, such as a 67% capital cost decrease per tonne of captured CO_2.[95]

CCUS refers to many different technologies, however, and they are in different stages of development. For example, later-stage commercial deployment support is needed for post-combustion capture methodologies for coal-fired power generation, which are well-understood. On the other hand, capture methodologies using membranes have applications for natural gas-fired power generation that will be critical as the use of natural gas continues to replace coal in the electricity sector. This research is in the demonstration stage. Similarly, research efforts in direct air capture and in carbon recycling (also known as non-EOR carbon utilization) are in relatively early stages and will need support from the lab scale through commercial deployment.

The wide scope of CCUS technologies means that some of the performance improvements and cost declines associated with deployment at scale of other technologies, from consumer electronics to renewable energy generation, may take longer to realize. Also, to date, there have been limited examples of commercial-scale deployment of CCUS technologies. Globally, there are currently 18 large-scale CCUS projects in operation,[96] and a few additional smaller capture projects at ethanol plants. Limited commercial-scale deployment will slow down progress on performance improvements and cost reduction.

For these reasons, it is important that the goals of Mission Innovation, launched at the same time as the Paris Agreement, are achieved. At that time, more than twenty nations agreed to double clean energy RDD&D over five years. Currently, nations are not on track to achieve this goal, although in some nations, budgets for clean energy RDD&D are increasing. At the end of 2016, the United States and Saudi Arabia launched the Mission Innovation Carbon Capture Innovation Challenge (MI CCIC), which identified 30 priority research directions in total for CO_2 capture, CO_2 utilization, CO_2 storage, and cross-cutting issues. MI CCIC is currently led by Saudi Arabia, Mexico, and the United Kingdom. The MI CCIC recently published the Accelerating Breakthrough Innovation in Carbon Capture, Utilization and Storage report, which could serve as a foundation for enhanced collaboration in this area.[97]

FINANCIAL INCENTIVES

While robust support for RDD&D can help achieve breakthroughs in next-generation technologies, financial incentives are needed to help deploy first-of-a-kind technologies at the commercial scale. Financial incentives can include a wide range of policies, such as tax credits, loan guarantees, tax-exempt bonds, grants, and feed-in tariffs. Many of these financial incentives have been used successfully to accelerate the deployment of renewable energy technologies, such as wind, solar, and geothermal energy. Often, multiple, overlapping financial incentives will be needed to help a number of initial commercial-stage projects come online. This initial push can position an industry to develop economies of scale in manufacturing and to identify lessons learned in construction and operation that can lead to performance improvements and cost declines. Policy parity with other forms of clean energy generation could help accelerate deployment of CCUS technologies. The unique role that CCUS technologies can play in the industrial sector and the critical role of BECCS and direct air capture warrant a closer look at domestic policies to determine whether financial incentives could be enhanced. Policy parity is an important goal for these types of technologies.

In February 2018, the United States achieved a major milestone in domestic CCUS policy. The Section 45Q tax credit for CCUS technologies was extended and expanded. Previously, an industry-wide cap on available credits deterred financial investment in CCUS projects. After the passage of the Furthering carbon capture, Utilization, Technology, Underground storage, and Reduced Emissions (FUTURE) Act, the value of the tax credit was increased, it was made applicable to non-EOR carbon utilization projects and direct air capture for the first time, and the credit is now available for any qualifying CCUS project which commences construction by Jan. 1, 2024, after which point it may be claimed for 12 years. Analysis of the tax credit prior to its enactment found that it could lead to the annual storage of 50 million metric tons of U.S. power sector CO_2 emissions by 2030 and 70 million metric tons by 2040.[98]

CLEAN ENERGY STANDARDS

Similarly, clean energy standards can be used to encourage the development of CCUS technologies. More than half of U.S. states have established Renewable Portfolio Standards, which require that a certain share of electricity generated within a state originate from renewable sources like wind and solar energy. These standards could be expanded to include CCUS, as a handful of states have done, such as Massachusetts, Ohio, and Illinois. Unfortunately, to date, this policy has not driven CCUS deployment, which may be because of the scale of the financing gap. Some of these states, such as Ohio and Massachusetts, later revised the standards to reduce the allocation for CCUS or to let it expire completely. Therefore, it is likely that to be effective, clean energy standards with CCUS will also need the implementation of multiple, overlapping financial incentives to drive CCUS deployment. National energy plans could be similarly structured to include CCUS technologies. The expansion of these standards to include CCUS technologies would help create a market for CCUS technologies.

ENABLING LEGAL AND REGULATORY FRAMEWORKS TO MANAGE OWNERSHIP AND STORAGE OF CAPTURED CO_2

While many energy projects face challenges related to permitting, given the relative newness of CCUS projects for climate change mitigation, it can be especially difficult in some jurisdictions for CCUS projects to complete the permitting process in a timely manner. Furthermore, in areas where CO_2-EOR has been practiced for decades, ownership and liability for stored CO_2 is often well-settled and is often negotiated through contracts. Since the geological storage of CO_2 as a climate mitigation technique is a relatively newer phenomenon, ownership and liability for CO_2 stored in that context is often not as well-settled. In the United States, some states like Illinois and Louisiana set up CO_2 storage trust funds to address long-term liability issues. Generally, fees on operators of CO_2 storage sites would go into the trust fund. In exchange, at a certain point, liability for the stored CO_2 would transfer from the operators to the state. These structures are largely theoretical because some of these statutes, like that of Illinois, have expired.

In addition, in the United States, states have jurisdiction over property laws so there is often a patchwork of different regulatory regimes. For example, in many states, property rights for the surface can be severed from property rights to the subsurface. Some states have established regimes to pool subsurface pore space in cases where the pore space is large enough to be beneath several surface properties. Other nations may have other arrangements, such as where the government owns the subsurface. For example, in the Canadian province of Alberta, pore space is the property of the Crown in right of Alberta (a term of art under Canadian law).[99] To scale up CCUS deployment, these types of legal and regulatory issues need to be addressed in order for private sector investment to occur.

FINANCE: STATUS AND OPTIONS

Policies supporting broader deployment of CCUS technologies will succeed only if they are effective in mobilizing finance at the scale needed. Early projects have relied on a combination of public and private capital and – in some cases – on a revenue stream generated by the sale of the captured carbon. New business models, multilateral development banks and private finance must all play a role in scaling up CCUS investment.

COMMERCIALIZING CARBON RECYCLING

Project developers have in some cases been able to secure investment in CCUS projects through innovative business models. Currently, the most widely deployed commercial option to re-use CO_2 is CO_2-EOR. The opportunity for CO_2-EOR depends on the presence of declining oil reservoirs or residual oil zones, which may not be present in all nations. However, on a global basis, CO_2-EOR could deliver anywhere between 60 Gt to 360 Gt of CO_2 storage by 2050, depending on the extent to which CO_2 storage is maximized as oil is produced.

A well-known example is the NRG Energy Petra Nova project near Houston, Texas. Petra Nova – the first commercial-scale coal-fired power plant retrofitted with carbon capture technology in the United States and the largest post-combustion capture facility in the world – can capture 1.4 Mt of CO_2 a year. The Petra Nova project combined both public and private capital, receiving funds from the 2009 Recovery Act. The project also benefitted from Private Activity Bonds that are exempt from Federal taxation and were issued for commercial activity in areas affected by Hurricane Rita. The project developers created a joint venture with Japanese energy companies, obtained low-cost financing from Japan, and integrated the carbon capture and CO_2-EOR aspects of the project so that the profits from the CO_2-EOR activity could offset the capture costs.

One challenge facing CO_2-EOR has been declining oil and natural gas prices resulting from the widespread adoption of unconventional oil and gas development. In the United States, multiple proposed CCUS projects involving coal gasification were not completed because market dynamics changed so dramatically.

There is growing attention on the several forms of carbon recycling (or non-EOR carbon utilization) that could provide alternative revenue streams for the captured carbon. The five largest potential opportunities in terms of CO_2 emissions reduction by 2030 are: aggregates (0.3 -3.6 billion tons), fuels (0.07 - 2.1 billion tons), concrete (0.6 – 1.4 billion tons), methanol (0.005 – 0.05 billion tons), and polymers (0.0001-0.002 billion tons).[100] The five largest potential opportunities in terms of annual revenue by 2030 are: concrete ($150-$400 billion), fuels ($10-$250 billion), aggregates ($15 - $150 billion), polymers ($2-$25 billion), and methanol ($1 - $12 billion).[101] The potential for subsurface storage of CO_2 is much greater than storage through carbon recycling, but scaling up carbon recycling could help close the gap between the Paris pledges and the goal of limiting climate change to a two-degree Celsius increase from pre-industrial levels.

There is growing interest among stakeholders and the general public in carbon recycling, due in part to the success of the NRG COSIA Carbon XPRIZE, in which teams from the United States, Canada, the United Kingdom, India, and China are competing to identify carbon recycling options. The teams are working with CO_2 captured from coal- and gas-fired power plants at the Wyoming Integrated Test Center in the United States and the Alberta Carbon Conversion Technology Centre in Canada, respectively. Commercial viability is one of the criteria by which their projects will be judged. Some stakeholders are also interested in carbon recycling options for carbon captured from the atmosphere (direct air capture). For example, Carbon Engineering in British Columbia, Canada, is developing an "Air-to-Fuel" technology that combines CO_2 captured from the atmosphere and hydrogen from the electrolysis of water to produce synthetic liquid fuels. There could be an option in the future to "green label" fuels made from captured carbon, in order to harness the power of consumer choice.

CCUS FINANCING BY MULTILATERAL DEVELOPMENT BANKS

In developing nations, CCUS project developers may also be able to seek funding from multilateral development banks (MDBs). In 2009, the World Bank established a CCS Trust Fund, funded by the United Kingdom, Norway, and the Global CCS Institute, to build capacity in developing nations for CCUS technologies. The Asian Development Bank also has a CCS Trust Fund. To date, $55.8 million has been allocated from the World Bank CCS Trust Fund.[102] Phase I of the World Bank CCS Trust Fund allocated $7.9 million to support capacity building for CCUS technology deployment in nine countries and regions: Botswana, South Africa, China, Mexico, Indonesia, Kosovo, Egypt, Jordan, and the Maghreb region of North Africa.[103]

Phase II of the World Bank CCS Trust Fund supported CCUS pilot projects in Mexico and South Africa. The World Bank CCS Trust Fund provided $20.5 million and the Mexican government provided $12.5 million for the Poza Rica CO_2 capture project which will capture roughly 20 tons of CO_2 per day from a natural gas combined cycle power plant and the Brillante oil field CO_2 storage and EOR monitoring project.[104] In South Africa, the World Bank CCS Trust Fund provided $27.4 million and the South African government provided $15 million for pilot projects for CO_2 capture and storage near Pretoria.[105] In the future, the World Bank CCS Trust Fund could be used to fund capacity building for CCUS projects in the industrial sector, such as in steel and cement production and at refineries and it could be used for CCUS projects with biomass.[106] The Asian Development Bank has also partnered with the United Kingdom to support CCUS technologies in China and Indonesia.

At the same time, historically, CCUS projects have not been a top priority for most MDBs. For example, the World Bank Group's Climate Change Action Plan for 2016-20 does not reference CCUS technologies.[107] However, in the context of international agreement around a two-degree Celsius goal and net zero emissions in the second half of the 21st century, as well as expert analysis showing that CCUS deployment will be critical for achieving that goal, there may be more of an opportunity now to prioritize investment in CCUS projects.

Other MDBs have included CCUS in their strategy documents. In its Climate Change Operational Framework for 2017-2030, the Asian Development Bank explains:

> *As fossil fuels account for over two-thirds of developing Asia's emissions, the region's low-carbon transition must start with the energy sector. In the 2°C scenario, by 2050, the region can cut its emissions by nearly half through less carbon-intensive energy production, notably by deploying renewables such as wind, solar, and biomass, and through carbon capture and storage. An ambitious mitigation effort leaves little room for new coal capacity in Asia that does not include carbon capture and storage.*[108]

This pragmatic approach from the Asian Development Bank would benefit from partnership with additional MDBs, including a commitment to jointly prioritize and fund CCUS projects. To that end, it would be helpful to develop engagement strategies to encourage MDBs to prioritize CCUS technologies.

PRIVATE SECTOR FINANCING CHALLENGES AND OPPORTUNITIES

In the energy sector, many oil and gas companies have self-funded research in CCUS technologies. For example, in 2016, Exxon launched a partnership with Fuel Cell Energy to conduct a demonstration project using carbonate fuel cells paired with coal- or natural gas-fired power plants. Similarly, companies that use CO_2-EOR technology have been conducting their own research to maximize oil production and minimize costs. The extension and expansion of the Section 45Q tax credit in the United States is also leading to more investment in CO_2-EOR projects. In June 2018, Occidental Petroleum Corporation and White Energy announced a partnership to evaluate the feasibility of a CCUS project at ethanol plants in Texas, where the captured CO_2 would be used for EOR in the Permian basin.[109]

The Oil and Gas Climate Initiative (OGCI) – a partnership of more than 10 major oil and gas companies – recently announced investments in Inventys, a Canadian next-generation capture technology company, and Econic, a CO_2 utilization company that will convert captured carbon into polyols, which are the basis for polyurethanes used in many industries, from building materials to appliances to car parts.[110]

However, scaling up CCUS deployment will require moving beyond self-financing of research efforts and attracting significant long-term investment from the finance industry. Barriers to private investment include the lack of clear policy drivers, public perceptions about the risks associated with carbon capture and storage, and uncertainty about ownership and liability related to stored CO_2, especially for pure saline storage projects, where the legal and regulatory frameworks are often not as well-developed as the CO_2-EOR framework.[111]

In the United States, litigation around and regulatory reversal of policies established by the U.S. Environmental Protection Agency under the previous administration may be having a chilling effect on private sector investment in climate mitigating technologies. In addition, CCUS technologies are controversial in many nations, because there is concern that they represent "greenwashing" of conventional technologies. Some have conflated risks of induced seismicity associated with unconventional oil and gas development (e.g., hydraulic fracturing) with risks from CO_2-EOR. Others are concerned that the world's nearly fifty years of experience with underground injection of CO_2 is too short compared to the need to store CO_2 for millennia. Some would prefer to close down coal- and gas-fired power plants rather than retrofitting them with CCUS in order to limit non-CO_2 air pollution. Cumulatively, these concerns have created a reputational risk with association with CCUS technologies.

As a result, private sector banks have been reluctant to invest in CCUS projects. Even though studies have outlined the need for trillions of dollars of investment of private capital by 2030 to achieve the U.N. Sustainable Development Goals, there is a lot of competition for private investment in energy access and clean energy technologies, so CCUS projects have received relatively little attention.

There may be opportunities for further engagement and investment by private sector businesses. Many private sector banks have published corporate sustainability reports and have identified renewable energy goals and targets. Investments in CCUS projects could help achieve the broader sustainability goals described in these corporate sustainability reports. Financial sector renewable energy goals and targets could be expanded to include

CCUS technologies.

Across many sectors, corporate procurement of renewable energy has also increased significantly. Some engagement by financial institutions with their clients on sustainability practices is taking place already. The G20 Financial Stability Board Task Force on Climate-related Financial Disclosures issued recommendations in 2017 for financial institutions that include describing their engagement with their clients to push for sustainability measures. To the extent this activity is taking place, private sector banks could encourage their corporate clients to broaden their clean energy procurement goals to include CCUS. By engaging private sector businesses on their existing initiatives, it may be possible to facilitate a dialogue that could strengthen public-private cooperation. This is a critical step for accelerating CCUS deployment.

COLLABORATION: STATUS AND OPTIONS

With implications for both policy and finance, there are several major international efforts to collaborate on RDD&D of CCUS technologies, including the Carbon Sequestration Leadership Forum (CSLF), the IEA and IEA Greenhouse Gas R&D Programme (IEAGHG), the CCUS initiative under the Clean Energy Ministerial (CEM), and the MI CCIC. There are also several regional efforts to collaborate on carbon capture RDD&D,[112] three international CCUS test centers,[113] multiple bilateral research partnerships that include a carbon capture focus,[114] the Global CCS Institute, and the Oil and Gas Climate Initiative.

These collaborative efforts have facilitated international knowledge sharing about CCUS technologies and have raised the profile of CCUS technologies. For example, the newest international collaborative effort on carbon capture RDD&D was launched at the CEM, which is a forum of 25 nations and the European Commission focused on advancing the deployment of clean energy technology. At CEM 9, the May 2018 meeting in Copenhagen, Denmark, the United States announced an initiative to strengthen the framework to build collaborative partnerships between the public and private sectors on CCUS technologies. The leaders of the initiative are the U.S, Norway, Saudi Arabia, and the United Kingdom and participants include Canada, China, the European Commission, Japan, Mexico, the Netherlands, South Africa, and the United Arab Emirates. Some of the future activities under the initiative include sharing of carbon capture knowledge through webinars and online resources; the development of models, tools, and evaluation methodologies; and technical training and peer-to-peer consultation.

In addition, in 2017, the CSLF updated a Roadmap outlining priority areas for research and collaboration. The CSLF also established several Technical Group task forces focused on offshore CO_2-EOR, BECCS, improved pore space utilization, and non-EOR utilization as well as Policy Group task forces focused on regulatory issues, communications, and financing. Many of these efforts would benefit from high-level focus from ministers, heads of government, and private sector CEOs at high profile events like G20 meetings.

OPPORTUNITIES AT THE G20 TO RAISE AWARENESS AND BUILD CONSENSUS

The 2019 G20 Summit and energy and environment ministerial meeting in Japan, which will take place on June 28-29, 2019 in Osaka and June 15-16, 2019 in Karuizawa respectively, could be promising venues to raise the profile of CCUS, make progress on shared commitments, and strengthen existing collaborative efforts. In his January 2019 speech in Davos, Switzerland, Japanese Prime Minister Shinzo Abe highlighted that disruptive innovation to address climate change, including technologies such as carbon recycling, would be important themes at the G20. The G20 has addressed climate change before. In 2009, the G20 agreed to phase out subsidies for fossil fuels over the medium term.[115] In 2016, the United States and China were seen as jointly leading a focus on climate change at the G20 summit. In 2016, the G20 Financial Stability Board also created a Task Force on Climate-related Financial Disclosures, which issued final recommendations in 2017 to improve corporate reporting of climate-related risks and opportunities in mainstream financial filings. Given the multiple benefits of CCUS, including its critical role in reducing greenhouse gas emissions, creating and protecting jobs, creating new supply chains, preserving industrial regions, boosting economic growth, and promoting energy security, options to accelerate CCUS deployment may address many priorities of G20 nations at once.

POLICY

The 2019 G20 meetings could offer opportunities to fill in existing gaps in collaboration by taking on new activities related to policy. For example, **G20 nations could agree or be encouraged to prepare national readiness assessments or action plans for clean energy technologies. In the section on CCUS, these documents could include a legal analysis of measures needed to facilitate commercial deployment of large-scale CO_2 storage**, **an internal analysis of other domestic policies that could incentivize CCUS and create a level playing field for clean energy technologies, and a business model analysis to determine what types of partnerships and arrangements would best facilitate deployment**. A task force could be created as a mechanism to ensure that the work would be carried forward towards G20 meetings in 2020 and beyond. G20 nations represent a wide variety of legal traditions, so each G20 nation would need to conduct its own analysis to determine how to address issues of ownership and liability for stored CO_2. Certain countries, like Australia, are considered to have advanced frameworks that would support CCUS development.[116] Others could consider how to update their frameworks consistent with their legal principles. Moreover, since some large-scale CO_2 storage projects might be regional in nature, it would also be useful to conduct legal analysis of how cross-border projects could be implemented. Similarly, many nations have strong policies to incentivize renewable energy generation and there may be opportunities for similar policies to incentivize CCUS technologies. Strong financial incentives, like the U.S. Section 45Q tax credit, can be particularly powerful in driving project deployment. Finally, each G20 nation allows for different business models for energy or industrial sector companies. In some nations, there are state-owned corporations in the energy sector and in other nations, the energy sector is fully private, although it may respond to public sector incentives. As a result, business models for CCUS technologies could differ in each country. The results of the national readiness assessments or action plans could be presented at the next G20 meetings.

At the same time as opportunities to improve legal, regulatory and policy regimes are pursued, better engagement of non-OECD countries around prioritizing CCUS deployment should continue. For example, several nations have included CCUS technologies in their Nationally Determined Contributions (NDCs) under the Paris Agreement. Beyond that, **the G20 may present an opportunity for more nations to include CCUS technologies in their long-term strategies under Article 4 of the Paris Agreement, as well as in future Technology Needs Assessments.**

Attention could also be called to expedite international policy efforts, such as the efforts at the International Standards Organization to develop, maintain, and update standards related to CCUS and the development of the Paris Agreement Article 6 carbon markets rules. On ISO standards, the goal would be to standardize accounting for the carbon dioxide stored through CCUS technologies, so that CCUS projects could sell credits that could be traded in markets created under the United Nations Framework Convention on Climate Change. CCS projects are eligible under the Kyoto Protocol's Clean Development Mechanism and as the rules for the Paris Agreement Article 6 carbon markets are developed, it would be helpful if CCUS projects were eligible under this framework as well.

FINANCE

At the G20 meetings, there could be a focus on more directly engaging and educating financial institutions, including multilateral development banks and private sector banks. **Given ongoing needs to build technical and financial capacity for pilot-scale and eventually commercial-scale CCUS projects, there is an opportunity at the G20 for nations to increase funding for the CCS Trust Funds of the World Bank and the Asian Development Bank and for private sector banks to partner with these CCS Trust Funds through risk-sharing agreements to amplify the impact of their investments. MDBs could also more frequently provide updates at G20 meetings on how CCUS technologies can help achieve their goals with respect to climate change, such as at annual side events.**

Perhaps more importantly, there also is an opportunity to engage with private sector financial institutions around their sustainability and clean energy commitments to encourage them to consider prioritizing CCUS. Certainly, private sector financing of CCUS projects will likely require further development of legal and regulatory frameworks for the ownership and liability of stored CO_2, domestic policy that incentivizes investment in

CCUS, and an understanding of business models that can make CCUS project economics work. In recognition of the importance of including CCUS in clean energy portfolios, there is also a need to change the narrative around CCUS technologies. Instead of only focusing on the costs of CCUS, the value of CCUS should be highlighted. **In the Ministers' Communique, G20 leaders could consider highlighting the multiple benefits of CCUS, such as CO_2 emissions reduction in the power and industrial sectors, improving access to power and water in developing nations in particular, the creation and preservation of jobs, the creation of new supply chains, the preservation of industrial regions, economic growth, and energy security. Side events could be developed to highlight recent CCUS technology milestones at operational projects, new private sector investments in CCUS projects, and opportunities for further cost reduction based on these milestones**. **Press engagement and social media outreach could help educate the public on the value of CCUS technologies**.

INTERNATIONAL COLLABORATION

The G20 meetings also could offer opportunities to make progress on shared commitments to advance CCUS technologies. In 2017, the CSLF published an updated Roadmap for CCUS technologies with specific near-term, medium-term, and long-term recommendations for CO_2 capture, CO_2 infrastructure, CO_2 storage, and CO_2 utilization, including CO_2-EOR. These recommendations are described in the Appendix. Many of the goals and action items from the Roadmap could be elevated at the 2019 G20 meetings. The 2019 G20 meetings are well-suited to highlight CSLF Roadmap goals and action items that require high-level buy-in, international collaboration, and that have the potential to significantly improve public perception of CCUS technologies. There may be limited appetite for the creation of a new venue or forum for CCUS. Therefore, using existing meeting venues and forums might be preferable in some cases. For example, goals and action items of a highly technical nature are likely better suited to continued efforts in existing forums, like CSLF or MI CCIC. Moreover, there may even be an opportunity at the G20 meetings to coordinate among the different CCUS work streams in existing forums and review how these could be streamlined.

1. *Expanding Funding for Existing Collaborations*

   The CSLF 2017 Roadmap highlights existing collaborative efforts on CO_2 capture and CO_2 storage that would benefit from additional funding. Also, at CEM 9, the United States and Norway announced a CCUS data-sharing consortium that includes the U.S. Department of Energy, the Norwegian CCS Research Centre, the Norwegian Programme for Power Generation with Carbon Capture and Storage (Climit), Gassnova, and several private sector and academic partners, like Equinor (formerly Statoil), the University of Illinois, SINTEF and IEAGHG. **At the G20, a commitment to expand and better fund the International Test Centre Network and the CO_2 Storage Data Consortium could be announced.**

   This would reaffirm the shared consensus around the CSLF 2017 Roadmap and the CO_2 Storage Data Consortium and signal that G20 nations have confidence in these efforts. To support these requests for funding, the organizers of these collaborative efforts could provide a baseline analysis of the work that has been accomplished to date and how further funds could amplify their impact. Expanding funding for these collaborations would facilitate continued global public-private partnerships between researchers in academia, government and industry, which will be beneficial as CCUS deployment increases.

2. *Facilitating Large-Scale CCUS Chains*

   In the near-term, transferring captured carbon dioxide between countries will be a challenge under existing law, because carbon dioxide is currently classified as waste, which cannot be exported for offshore storage. **There is an urgent need for nations to ratify the amendment to the London Protocol to allow CO_2 to be exported for offshore storage and this could be incorporated into statements made by the leaders of G20 nations at the 2019 G20 Summit and/or the energy and environment ministerial meeting.**

   In addition, focusing on cross-border CCUS projects is especially important because the subsurface often crosses national boundaries. **The G20 could be an opportunity to facilitate large-scale CCUS chains, including cross-border CCUS projects**. A task force could be created to identify opportunities for large-scale CCUS chains in several geographic regions, prioritizing industrial hubs and clusters. The task force could report back at subsequent G20 meetings with more information on these opportunities and could make this information available to private investors. This task force would enable high-level collaboration on planning, financing, and building out trunk pipelines that could connect multiple sources of CO_2 to storage sites.[117] This could include cross-border transportation of CO_2 by marine transportation or through pipelines.

Building on discussions at the November 2018 International CCUS Summit hosted by the United Kingdom and IEA, more work could be done to determine whether CO_2 transportation can be decoupled from CO_2 capture projects so that various public-private and multi-government partnership structures could be developed for each piece.[118] A high-level focus from heads of government would elevate the issue dramatically garnering more public attention on the recommendations of the task force.

3. Maximizing CO_2 Storage Through Carbon Recycling

CO_2-EOR is the most commercially demonstrated example of CCUS technologies, dating back almost 50 years, and it is also arguably the most controversial example of CCUS. Additionally, carbon recycling (also known as non-EOR carbon utilization) has drawn a lot of popular attention because of its innovative nature and because it appeals to stakeholders looking for opportunities to monetize manmade carbon captured from the atmosphere.**A new carbon recycling initiative by G20 nations to create a task force with representatives from major businesses to explore options to gauge consumer interest and consider how to create markets and supply chains for building materials, products and fuels made from captured carbon would be helpful.**

It would also be consistent with the priority identified at the November 2018 International CCUS Summit hosted by the United Kingdom and the IEA of "unlocking the value of CO_2".[119] Areas that could be explored include better disclosure of embodied carbon in the built environment and harnessing the power of the consumer to drive the market for products and fuels made with captured carbon. These methods of information sharing and "green labeling" could help create a market and revenue stream to offset capture costs. It would also reframe the public perception of CCUS technologies. The task force could also examine aspects of CO_2-EOR, such as how to maximize CO_2 storage in the current business environment to help demonstrate how CO_2-EOR can be a part of a transition to a lower-carbon economy. The task force's recommendations and leading options for carbon recycling could be presented at a conference that is open to the public and the press.

4. New Focus on Hydrogen Projects

Finally, a more ambitious option is to try to send a market signal about the commitment of G20 nations to CCUS to help increase the participation of financial institutions. For example, **much like the Paris Agreement signaled to investors that a transition is underway to a low-carbon economy, a G20 commitment to partner on a new dedicated focus on capacity building or demonstration projects in priority areas, such as hydrogen production from fossil fuels with CCUS, could encourage investor participation in CCUS deployment.**

There are multiple initiatives exploring hydrogen production from fossil fuels with CCUS. In October 2018, there was a Hydrogen Ministerial Meeting where key shared priorities were outlined in the Tokyo Statement, including coordinating and collaborating on hydrogen storage, infrastructure, and supply chains.[120] Japan and Australia are collaborating on a pilot-scale demonstration project to produce hydrogen from the gasification of lignite. The project developers may partner with CarbonNet, an ongoing CCS demonstration project, to store the CO_2. The hydrogen would be transported by boat to Japan, where it could be used for power generation, fuel cell electric vehicles, and residential combined heat and power. The Netherlands and the United Kingdom have also launched hydrogen initiatives.[121] In September 2018, countries in the European Union agreed to focus on opportunities for hydrogen in the transportation and power sectors in order to stay on track to meet 2030 emissions reduction goals.[122] A focus on hydrogen would have benefits for multiple sectors – power, industrial, transportation – as well as natural gas. The CSLF 2017 Roadmap also recommends a focus on capture projects involving hydrogen production.

CONCLUSION

In the last year, CCUS deployment has witnessed major milestones, such as the extension and expansion of the Section 45Q tax credit in the United States and new investments by the Oil and Gas Climate Initiative. These milestones reinforce the importance of the major efforts on international collaboration on CCUS, such as the CSLF, the CEM, and the MI CCIC. These efforts should be maintained but there is an opportunity to expand upon this foundation at the 2019 G20 meetings in Japan, by launching new initiatives and exploring opportunities to make progress on certain shared commitments identified in the CSLF 2017 Roadmap.

APPENDIX: SUMMARY OF CSLF ROADMAP RECOMMENDATIONS

One of the priority recommendations of the Carbon Sequestration Leadership Forum (CSLF) 2017 Roadmap is that there should be public and private sector collaboration to achieve:

- Long-term isolation from the atmosphere of at least 400 megatonnes (Mt) CO_2 per year by 2025 (or permanent capture and storage of in total 1,800 Mt CO_2)
- Long-term isolation from the atmosphere of at least 2,400 Mt CO_2 per year by 2035 (or permanent capture and storage of in total 16,000 Mt CO_2).

To that end, the CSLF 2017 Roadmap outlines the following recommendations for CO_2 Capture, CO_2 Infrastructure, CO_2 Storage, and CO_2 Utilization.

CO_2 CAPTURE

- By 2020, the Roadmap aims for a 30 percent capture cost reduction, an expansion of the International Test Centre Network (a forum for knowledge-sharing on CCUS), a resolution of specific issues related to capture from industrial sources and BECCS, a greater focus on non-solvent-based capture technologies, increased R&D support for new capture technologies, and more focus on hydrogen production with CCUS.
- By 2025, the Roadmap aims for a 40 percent capture cost reduction and more pilot scale (1-10 MW) funding of promising technologies.
- By 2035, the Roadmap aims for a 50 percent capture cost reduction and more experience integrating power plants with CCUS technologies into electricity grids that are also incorporating renewable energy.

CO_2 INFRASTRUCTURE

- By 2020, the public and private sectors should better characterize the impacts of impurities on CO_2 pipeline materials, better understand and prepare safety measures for CO_2 leakage from pipelines, optimize marine transport and offshore unloading processes for CO_2, secure steel manufacturing capacity for CO_2 pipelines, develop common monitoring and metering systems for CO_2 streams that may have different compositions and levels of purity, and identify business models for CO_2 transportation and storage companies.
- By 2025, the Roadmap aims for the development of three large-scale CCUS "chains" that are less than 10 Mt CO_2/year; one each in the power sector, the industrial sector, and BECCS; these chains would involve shared infrastructure.

By 2035, the Roadmap aims for further expansion of these CCUS chains and clusters.

CO_2 STORAGE

Large Scale CO_2 Storage

- By 2020, the public and private sectors should collaborate to better identify and characterize storage sites, maintain the Large-Scale Saline Storage Project Network, expand the use of the CO_2 storage data consortium, support R&D for case studies in CO_2 storage, explore synergies with geothermal energy, better research the transportation and storage interface, conduct regional appraisal programs that have dynamic calibration and matched source-sink scenario analysis, and improve public understanding of the safety of CO_2 storage.
- By 2025, the Roadmap aims for the storage of 400 Mt CO_2 per year which would be the capture and storage of 1,800 Mt of CO_2; characterization of large scale CO_2 storage sites that are linked to clusters for CO_2 transportation, the public availability of national CO_2 storage assessments for each CSLF member, continued development of execution and appraisal procedures in potential key storage basins, and the development of a workflow to demonstrate to regulators that site characterization is consistent with international best practices.
- By 2035, the Roadmap aims for the storage of 2,400 Mt CO_2 per year which would be the capture and storage of 16,000 Mt of CO_2.

Monitoring and Mitigation

- By 2020, the public and private sectors should collaborate to reduce costs for onshore and offshore monitoring, measuring and leakage detection, develop methods to remediate leaks, and identify minimum monitoring and verification requirements that could inform laws and regulations.

- By 2025, the Roadmap aims for a twenty-five percent cost reduction for monitoring and verification.
- By 2035, the Roadmap aims for a forty percent cost reduction for monitoring and verification.

Understanding the Storage Reservoirs

By 2020, the public and private sectors should collaborate to advance simulation tools; develop consistent methods for quantifying CO_2 storage capacity, including dynamic CO_2 capacity; improve steel and cement well materials, enhance prediction capability of storage efficiency based on successful projects, advance reservoir models on pressure buildup to enable the injection of large amounts of CO_2, develop workflow for fault integrity and caprock studies in CO_2 storage sites, and develop cost models to improve assessment of CO_2 storage sites.

CO_2 UTILIZATION

- By 2020, the public and private sectors should collaborate to develop a common understanding of how CO_2-EOR projects can transition to CO_2 storage under applicable laws and regulations; further demonstrate carbonate mineralization for the creation of useable products incorporating captured carbon; support research in catalysts, including nanocatalysts, to bring down costs; support research on subsea separation and mobility control; identify opportunities and conduct additional technology readiness assessments for non-EOR CO_2 utilization, including lifecycle assessments; better understand the CO_2 energy balances for non-EOR CO_2 utilization pathways.
- By 2025, the Roadmap recommends that additional offshore CO_2-EOR projects be conducted.

ENDNOTES

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