The Global Home of Chemical Engineers

Bridging the Finance Gap for Carbon Capture and Storage

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Executive Summary

Diverse stakeholders, including federal agencies, business interests, and the intelligence and defense communities, have recognized the importance of developing a global strategy to reduce greenhouse gas (GHG) emissions. One important part of this strategy will be reducing emissions from the electric power sector, which is the single largest contributor to U.S. GHG emissions. Yet, in the U.S. and globally, fossil fuels are projected to make-up over half of electricity generation for at least the next two decades. Consequently, carbon capture and storage (CCS), which is a technology to capture CO_2 emissions at large-scale stationary sources such as power plants and industrial plants, will be an important part of an overall GHG mitigation strategy.

Even in the absence of a comprehensive climate policy, carbon capture utilization and storage (CCUS) projects, where the CO_2 is recycled for industrial use, have advanced. The CO_2 is primarily used for enhanced oil recovery (EOR), which allows for the production of additional oil from depleted oil fields.

While each of the separate elements of CO_2 capture, transport, and storage are commercially available and have decades of operational experience, the integration and scale-up of these elements at large-scale power plants is still in the demonstration phase. At this early phase in technology development, government support is critical.

The major barrier to larger scale implementation of CCS is economic. Adoption of CCS above the amount supported by the market for EOR would likely require a price on carbon. And, current levels of governments support do not provide sufficient incentive for the private sector to invest in a new technology with its associated economic and technical risks.

This paper provides an overview of current policy support for CCS, which includes R&D funding, tax credits, and grants for demonstration projects. Both public and private sector stakeholders have important roles to play in promoting the development of CCS.

While debate continues about putting any price on carbon, Congress could, in the short term, provide a suite of incentives to support CCS deployment, including expansion of the CO_2 sequestration tax credits, establishment of a regulatory framework for long-term carbon storage liability, and appropriations for CCS demonstration projects that incorporate lessons from past projects. State governments could include CCS in low carbon portfolio standards to make it easier for regulated utilities to recover costs for CCS projects through rate increases. Finally, the private and public sectors should work together to develop new ways to finance and allocate the risk for CCS.

Introduction

The most recent report from the Intergovernmental Panel on Climate Change warned that, if GHG mitigation efforts are not undertaken, climate change could have pervasive and long-lasting impacts that include more frequent severe weather events, overall decreased agricultural yields, and flooding of coastal areas due to sea-level rise (*1*). The Third National Climate Assessment indicated that these impacts are already being felt, with the Northeast experiencing more extreme precipitation and the Southwest experiencing more droughts and wildfires (*2*). Business interests have also started to recognize the costs of delaying action on climate change. In its report, the Risky Business Project, a group which focuses on quantifying the economic risks of climate change, identified damage to coastal property and infrastructure, climate-driven changes in agricultural production and energy demand, and the impact of higher temperatures on labor productivity and public health as the most significant risks to businesses (*3*).

The implications of climate change are even being considered by the intelligence and defense communities, which have concluded that climate change could foster political instability by exacerbating competition for scarce resources (*4*).

While the U.S. and other industrialized countries are responsible for the majority of cumulative GHG emissions, the adverse effects of climate change will likely fall disproportionately on developing countries, which lack the financial resources and infrastructure required for adaptation (*1*).

A final incentive to adopt GHG mitigation measures is averting so-called "tipping points," which are temperature thresholds that may lead to irreversible, large-scale changes, such as melting of Arctic sea ice and extinction of a large percentage of marine and terrestrial species (*5*). In this context, climate change mitigation can be viewed as an insurance policy to reduce the probability of worst-case scenarios (*5*).

Stabilizing GHG emissions requires reducing emissions from the transportation, industrial, residential and commercial, and electric power sectors. Many policy initiatives have focused on decarbonization of the power sector. Not only did it account for 28 percent of U.S. CO_2 emissions in 2013, making it the single largest CO_2 source, but it is also the most cost-effective sector to decarbonize, due to the number of low carbon electricity generation options available (*6*). The Energy Information Administration forecasts that in 2040, coal and natural gas will still provide 65 percent of U.S. electricity generation (*6*) Globally, it is estimated that coal and natural gas will constitute 55 percent of electricity generation in 2040 (*7*).

The implication of using coal and natural gas to meet energy demand in the next two decades is that much of the electricity-generating infrastructure and its associated emissions will be locked in, since large power plant installations are capital-intensive and long-lived.

Fossil fuels will continue to contribute to the energy mix because they have several important advantages. Coal is abundant and widely distributed, which means that many countries have an energy security motivation to rely on domestic coal reserves. Coal is also one of the cheapest forms of energy. In addition, coal's high energy density allows it to be produced, transported, and stored with relative ease – unlike, for instance, the electricity produced from rooftop solar panels, which must be used instantaneously, in the absence of massive electrical storage systems.

In the U.S., natural gas has recently emerged as an attractive fuel source for power plants, due to technical advances that have led to a surge in domestic natural gas production. Because electricity produced from natural gas-fired power plants reduces CO_2 emissions by about one-half compared to coal-fired power plants (*8*), natural gas has also won support from some environmental groups, who view it as a bridge fuel that can ease the transition to renewable energy. In addition, natural gas power plants can easily vary their outputs, allowing them to cost-effectively back up intermittent renewable sources when there is not enough wind or solar energy to meet electricity demand (*9*).

In light of the need to reduce GHG emissions form the power sector while continuing to rely on coal and natural gas for electricity generation, carbon capture and storage (CCS) is a critical technology, since it allows for emissions reductions from the existing stock of coal- and natural gas-fired power plants. While there has been a focus on deploying CCS at coal-fired power plants, since these make up about three-quarters of emissions from the U.S. power sector (*6*), CCS can also reduce emissions from natural-gas fired power plants and industrial processes where concentrated CO_2 streams are produced, such as steel production and natural gas processing (*10*).

Of equal importance, there are no fundamental technological or physical barriers to commercial-scale deployment of CCS. Industry already has decades of operational experience managing each of the individual elements of CO_2 capture, transportation, and storage; the main challenge remaining is integrating and scaling up these elements cost-effectively.

Numerous models have shown that GHG mitigation would be costlier and more challenging without CCS. According to one model, the most cost-effective way of limiting global mean temperature increase to 2°C (*1)* would require equipping more than 40 percent of global coal-fired power plants with CCS (*7*). Another model found that if CCS was removed as a technology option, the capital investment required would increase by 40 percent relative to the baseline case where all technologies are available (*11*). CCS is projected to be especially important in developing countries, where most of the new fossil fuel-fired power plants will be constructed. In fact, by 2050, developing countries will need to account for 70 percent of the carbon captured by mass to satisfy the 2°C target (*11*). In a carbon-constrained world, CCS is a crucial option to have available.

TECHNOLOGY OVERVIEW

CCS can be broken into four components: capture, transport, utilization/storage, and site monitoring. In the absence of a comprehensive climate policy, carbon capture utilization and storage (CCUS) projects, which are a subset of CCS projects where CO_2 is recycled for industrial use, have advanced more quickly. (Note: in this paper, the term CCS will be used as a more general term to describe the technology and its application.) The primary use of CO_2 has been for enhanced oil recovery (EOR), where the CO_2 is injected into depleted oil fields to produce more oil.

Capture

At the power plant or industrial plant, CO_2 must be separated from the effluent stream, which is a mixture of gases, and compressed to lower the density. Technologies to separate gases are used in industrial hydrogen production, natural gas separation, and air separation (*10*).

Transport

Next, the compressed CO_2 must be transported via pipeline to the storage reservoir. Currently, approximately 50 million tons (Mt) of CO_2 per year are transported via pipeline in the U.S, which, for comparison, is equivalent to one-fortieth of all CO_2 emissions produced from burning fossil fuels for electricity in the U.S. (*6*). The vast majority of the CO_2 transported is used for EOR (*12*), which is a mature technology that dates to the early 1970s and currently accounts for 4 percent of total U.S. crude oil production (*13*).

Utilization/Storage

CO_2 must be injected into underground reservoirs, where it can be stably trapped for centuries to millennia, as has been seen with large-scale natural CO_2 formations (*12*). In addition, three large-scale CCS projects (Statoil Sleipner, Statoil Snøhvit and BP In Salah) have injected CO_2 underground with continuous monitoring for up to 14 years (*12*). There are also beneficial uses for CO_2 in industry, most notably in EOR, but other uses are the focus of current research efforts (*14*). Estimates of CO_2 storage potential are high, with studies indicating that, in the U.S. alone, there is enough capacity to store CO_2 emissions from the U.S. coal sector for the next thousand years (*12*).

Most of this capacity is in saline formations, which are underground reservoirs sealed by an impermeable layer of cap rock that prevents the CO_2 from escaping (*12*). These amounted to approximately 2,000 Mt of CO_2 in 2013.

Measuring, monitoring and verification

Carbon dioxide storage sites must be monitored to ensure that the CO_2 remains underground, both to ensure effective emissions reduction and to avoid potential harm to the environment or human health and safety (*12*).

TECHNOLOGY STATUS

Demonstration projects that integrate CCS elements in a large-scale power plant facility are still in the early development phase, with SaskPower's Boundary Dam in Canada the first such project to become operational in October 2014 (*15*). As of February 2014, there were 21 active, large-scale CCS projects globally that collectively stored 40 Mt CO_2 per year (*16*), which amounted to only 2 percent of all CO_2 emissions produced from burning fossil fuels for electricity in the U.S. in 2013 (*6*). In North America, all of the large-scale projects that have succeeded in becoming operational are CCUS projects that capture CO_2 for use in EOR, which offers a revenue stream independent of government subsidies (*16*). However, if CCS is to be deployed on a scale large enough to make a significant contribution to GHG mitigation, then the majority of the CO_2 will need to be sequestered in saline formations.

CCS TECHNOLOGY PATHWAYS

CCS technologies can be classified as either pre-combustion or post-combustion, with the type of technology determining the cost. In post-combustion capture, the CO_2 produced from burning coal or natural gas is dissolved in a liquid chemical solvent. This solution is then heated to separate the solvent from the CO_2, which can subsequently be compressed and transported (*17*). The energy to regenerate the solvent and compress the CO_2 results in a reduction in the electricity output of the plant, also referred to as the energy penalty (*17*). The goal of demonstration projects is to show that technologies can be scaled up in an industrial setting. Oxyfuel combustion, a specific type of post-capture combustion, combusts coal with nearly pure oxygen (O_2) (*17*). While oxyfuel combustion requires an air separation unit to obtain the pure O_2, it is still estimated to potentially cost less than conventional post-combustion (*10*).

Pre-combustion capture requires a certain type of coal processing where the coal is first converted to a mixture of gases in an integrated gasification combined cycle (IGCC) plant. Because this process produces a more concentrated stream of CO_2, physical solvents, which require less energy for regeneration, can be used instead of chemical solvents to separate the CO_2 from the mixture of gases.

One of the drivers for CCS is that both post-combustion and pre-combustion technologies can be used to add carbon capture units to – or "retrofit" – existing fossil fuel power plants. However, there are technical and economic challenges with integrating CCS, since the base plant is optimized to run under a certain set of conditions. One study concluded that for coal-fired power plants, due to the high cost of a retrofit, a post-combustion retrofit combined with a plant rebuild to improve the efficiency of the plant would be more economic (*17*). An equally viable option would be an oxyfuel retrofit, which would add an air separation unit to allow the coal to be combusted with pure O_2. An IGCC retrofit would be the least expensive, leading some to conclude that IGCC plants are "capture-ready" (*17*). However, coal gasification is not currently cost-competitive with conventional units (*10*). In fact, there are currently only two large-scale, operational IGCC plants in the U.S. (*18*).

COSTS

Currently, CO_2 mitigation with CCS is more expensive than other decarbonization strategies, such as converting from coal- to natural gas-fired power plants, but cost reduction is a major focus of research. The cost of electricity produced from different sources can be compared through a parameter called the levelized cost of electricity (LCOE), which spreads out, or levelizes, the capital costs over the lifetime of the investment. The actual electricity rate paid by the consumer includes not just the LCOE, but also the costs associated with transmission and distribution.

For CCS coal-fired power plants, the LCOE is 37 percent to 95 percent higher than for a plant without CCS (*10*). An estimated 70 percent to 90 percent of this cost increase is associated with capturing and compressing the CO_2 (*12*) and can be broken down into two main factors. First, additional capital investment is required for the separation and compression equipment. Second, for all of the carbon capture pathways outlined above, there is a significant, associated energy penalty.

In order to maintain the same electricity output, a power plant with CCS would need 16 percent to 30 percent more primary energy, which poses an additional challenge for retrofits (*10*).

STAKEHOLDERS

Because CCS is still in the demonstration phase, which is associated with significant technical and cost uncertainties, CCS projects rely on government funding and incentives to be financially viable. Consequently, both public and private sector stakeholders have important roles to play in advancing CCS development.

Public sector stakeholders

Department of Energy (DOE)

The Office of Fossil Energy in the DOE is responsible for administering research, development and deployment (RD&D) funding for CCS. The Office of Fossil Energy also operates the National Energy Technology Laboratory, where R&D efforts are centered.

Environmental Protection Agency (EPA)

The EPA regulates CO_2 storage under the Safe Drinking Water Act. It also regulates CO_2 emissions from new and existing power plants under the Clean Air Act.

Private sector stakeholders

Many private sector actors view CCS projects as risky. As such, they are reluctant to take on CCS projects without strong government support.

Power sector

Traditionally, the electric power sector has consisted of vertically integrated utilities that controlled the generation, transmission, and distribution of electricity. However, in the 1980s, there was a push for unbundling these services and allowing independent power producers to compete against each other in power generation (*19*). In the U.S., the structure of the electric industry differs from state to state. In regulated electricity markets, rates are subject to the approval of a regulatory commission, while in deregulated electricity markets, rates are determined by market forces. While utilities might be expected to be effective CCS project developers given their experience financing capital-intensive projects with long timescales, there is a sense of "treading water" due to the lack of a clear national climate policy (*10*).

Coal industry

The coal industry supports funding for CCS but is critical of EPA's proposed regulation of CO_2 under the Clean Air Act. The American Coal Council, which represents the coal industry, has opposed the EPA's proposed requirement that new coal-fired power plants use CCS because it does not consider CCS to have been adequately demonstrated (*20*).

Finance/banking

The project finance community, which includes commercial, government-backed, and "green" banks, is reluctant to take on CCS projects given the economic uncertainty and the fact that most of the underlying assets, such as the transport and storage infrastructure, would become worthless in the event of a project failure (*21*).

Interest Groups

Environmental groups

Environmental groups are divided, with some, including the National Resource Defense Council and the Environmental Defense Fund, supporting CCS as a necessary short-term decarbonization option because renewable energy sources are not scaling quickly enough (*22, 23*). However, others, such as Greenpeace and the Sierra Club, oppose the construction of any new coal-fired power plants due to environmental and human health impacts (*24*). These groups have also voiced doubts about whether the CO_2 can be stably trapped underground. In fact, the Sierra Club has mounted several legal challenges (*25*).

LACK OF ECONOMIC INCENTIVE

The CCS industry has consistently cited the lack of economic incentive as the most important reason for project cancellations and the low number of projects in development. A survey of 27 actors in the CCS industry reported that 89 percent of respondents identified the lack of economic incentive as the main barrier (*10*). The economic barrier to widespread CCS deployment arises from two factors.

First, deployment of CCS above the amount supported by the market for EOR requires a price on carbon. Fundamentally, carbon pollution is an externality, which in economic theory is a cost that is not borne by market participants but instead by the larger public. The social cost of carbon is not factored into energy prices (*26*). Models used by the U.S. government put the social cost of carbon at $37 per ton of CO_2 emitted (*27*). While the exact number is subject to debate, the social cost of carbon is greater than zero, which is the default price in the absence of any carbon pricing mechanism. Putting a price on carbon would offer a stable, long-term economic rationale for private sector stakeholders to invest in CCS.

However, even if a carbon tax were implemented, economic and technical uncertainties are significant enough during the demonstration phase that government support would be needed to incent private sector investment. Even when EOR sales are included, there would be a cost gap that must be filled by government support.

But, current levels of program support do not offer enough economic incentive for the private sector to invest in CCS demonstration projects. Large-scale CCS projects are capital-intensive, often requiring more than $1 billion in up-front investment, and cost overruns would be expected. In addition to high costs, CCS projects are also constrained by their inability to increase revenue. In regulated electricity markets, raising rates requires regulatory approval, which is a legally fraught process. In deregulated electricity markets, where independent power producers have to compete with each other, raising rates could lower market share.

POLICY UNCERTAINTIES

A related consequence of the current system of funding CCS through direct public subsidies is the policy uncertainty that this system creates. Power plants are long-term investments with timescales on the order of several decades, and would-be investors are uncertain about the policy permanence of CCS program support (*21*). If Congress decided not to reauthorize tax credits, for instance, then investors might be forced to take a loss. Another policy uncertainty is whether the project developer or the federal government bears ultimate responsibility for the potential risks of long-term CO_2 storage, which could include increased occurrence of earthquakes, groundwater contamination, and harm to human health and the environment from CO_2 leakage (*28*). In more mature industries, such as the oil industry, the risk of low-probability, high-impact events can be managed through insurance or other risk allocation methods with financial models that quantify the risk. Because CCS is such a new technology, there is not yet a standard risk assessment model for CCS projects, which means that, from the finance industry's standpoint, they not worth taking on, no matter the price (*21*). Finally, a safe and reliable national CO_2 pipeline network requires federal policy that clearly delineates federal, state, and local government responsibilities (*13*).

COST UNCERTAINTIES

In the long run, analyses indicate that CCS is a cost-effective technology for achieving substantial global GHG emissions reduction. However, as one report states, "CCS has the reputation of a 'costly' technology due to the mismatch between short-term firm costs and long-term uncertain benefits" (*10*). In other words, as with the deployment of any new technology, there is uncertainty about the extent and speed of cost reduction. The theory behind cost reduction is that as technologies become widely adopted, equipment manufacturers and construction companies gain familiarity with these technologies and are able to reduce costs (*30*).

TECHNICAL CHALLENGES

Research focused on reducing costs can be divided into three main areas (*29*). Materials research aims to reduce the energy required to separate the CO_2 from the other gases. Process research is based on more energy-efficient integration of the CCS system into the plant. Equipment research focuses on minimizing the size of reactors and developing advanced manufacturing techniques such as pre-fabrication to lower the capital costs.

The U.S. has been a global leader in CCS, accounting for 56 percent of global investment since 2007 (*32*). Of the estimated 14 large-scale projects worldwide, 10 are in the U.S. (*32*). Government support has been critical to the development of the industry. Since fiscal year (FY) 2008, Congress has appropriated about $6 billion for CCS RD&D, with $3.4 billion coming from the American Recovery and Reinvestment Act ("Recovery Act") of 2009 (*33*). However, Congress stipulated a timeline for funds expenditure that many projects were unable to meet, resulting in nearly half of the appropriated Recovery Act funds being returned to Treasury (*15*).

PROGRAM GOALS

Program goals are based upon division of CCS technologies into three different classes of first-generation, second-generation, and transformational technologies based on cost (*35*). First-generation technologies are currently being demonstrated or are commercially available, with second-generation and transformational technologies in the pipeline.

Program goals for the commercialization of CCS have shifted since 2005, with DOE's original goal of 90 percent CO_2 capture at less than 10 percent increase in cost of electricity by 2012 (*15*) now expected by 2025 for second-generation technologies (*36*). The longer time frame reflects both the increase in power plant capital costs, which have risen more quickly than general inflation, and a more accurate understanding of the energy penalty imposed by CCS (*15*).

FEDERAL CCS BUDGETS

While R&D funding levels have remained relatively constant since FY 2010, at around $200 million, there has been no funding enacted for demonstration projects since that provided by the Recovery Act. However, the Office of Fossil Energy's FY 2016 budget request did indicate that initial efforts to address the technical challenges of carbon capture at a natural gas facility would be made in preparation for a future demonstration facility in 2020 that would capture more than 75 percent of CO_2 emissions from a power system of at least 50 MW (*37*).

TAX CREDITS

The Energy Policy Act of 2005 established tax incentives for CCS by adding Section 48A, which provided tax credits for advanced coal projects (defined as capturing and storing at least 65 percent of CO_2 emissions) and Section 48B, which provided tax credits for coal gasification projects (*38*). In addition, the Emergency Economic Stabilization Act of 2008 established the Section 45Q CO_2 sequestration credit, which amounted to $20 per metric ton of CO_2 stored in a saline formation and $10 per metric ton of CO_2 injected for EOR (*38*). To qualify for these tax credits, CO_2 emissions had to be measured at the source of capture and verified upon disposal or injection (*38*).

From FY 2006 through FY 2018, these tax credits are estimated to cost the federal government $2.3 billion; however, the actual number is likely to be lower due to cancelled projects and the lack of proposed projects (*38*). These tax credits are capped and competitively awarded, with the Section 45Q credit set to expire after 75 Mt of CO_2 have been sequestered. As of June 2014, 27 Mt of CO_2 had been allocated. Given the number of projects that have been cancelled, it appears that these tax credits do not provide enough incentive to justify the uncertainties and risks associated with CCS (*38*). In addition, because risky and capital-intensive projects tend to be developed on the balance sheets of separate project companies to minimize shareholder risk, the low tax burdens of these companies minimizes the impact of these tax credits (*39*).

EPA REGULATIONS

Under the authority of the Clean Air Act, the EPA has proposed two regulations to address CO_2 emissions from the power sector. The first, which was proposed in September 2013, is the New Source Performance Standard, which sets CO_2 emission standards for new power plants based on an assessment of available emissions control technologies (*40*). New natural gas plants can comply by using the most efficient generation technology, but new coal plants would be required to employ CCS (*41*). The standard has already attracted controversy and is likely to be challenged both by Congress and in the courts on the grounds that CCS has not been adequately demonstrated. Despite its controversial status, the standard is not expected to have a significant impact on CO_2 emissions or electricity prices, because coal-fired power plants are already uncompetitive with natural gas-fired power plants (*41*).

The second regulation is the Clean Power Plan, which would affect existing power plants. Proposed in June 2014, the Clean Power Plan would set a target for 2030 of a 30 percent reduction in CO_2 power sector emissions relative to 2005. The EPA would set state-level limits on CO_2 from existing fossil-fuel power plants, but the states themselves would determine the compliance strategy (*42*). Models by the EIA which compared the effect of the Clean Power Plan relative to the base case indicate that, initially, the Clean Power Plan would accelerate the transition from coal to natural gas and then, by 2020, would increase the percentage of electricity generated from renewable energy sources (*42*). The Clean Power Plan is not projected to affect the development of CCS, given the high costs of CCS relative to other compliance options.

RECOMMENDATIONS

If the U.S. is to meet the program goal of cost-effective commercial deployment of CCS by 2025 and retain its standing as a global leader in CCS, the country needs policies to incentivize private investment and maintain deployment momentum in light of recent setbacks. It's significant that, as of February 2014, all of the large-scale projects in North America that have become operational are CCUS projects with diversified revenue streams from EOR. New and creative business models are needed to enable commercial projects. The recommendations that follow are for the stakeholders with the greatest responsibilities in promoting the development of CCS.

A. FOR CONGRESS

Consider expansion and reform of Section 48Q CO_2 sequestration tax incentives to take into account lifecycle emissions and incentivize the use of CO_2 for EOR operations.

Carbon sequestration tax credits can be an effective policy mechanism, because they can incentivize CCS not just in the power sector but also in industrial processes where separation of CO_2 may be easier and, therefore, less expensive. In addition, deploying CCS increases the operating expenses for the plant, and tax credits provide a way for project developers to recover some of those costs. Finally, tax credits are only awarded once the CO_2 has actually been sequestered, which makes them more effective at promoting CO_2 emissions reductions.

Currently, tax credits may be awarded for every ton of CO_2 that is sequestered for qualifying projects. However, when the emissions associated with the capture and compression of CO_2 are taken into account, the net emissions reduction is lowered by a factor of two. A standardized accounting framework that takes into account lifecycle CO_2 emissions, such as the one developed by the Center for Climate and Energy Solutions (*43*), would incentivize project developers to reduce CO_2 emissions at every step in the CCS chain. However, consideration of lifecycle emissions may necessitate increasing the tax credit so that there is still sufficient incentive for CCS project developers.

In May 2014, then Senator Jay Rockefeller (D-WV) introduced Senate Bill S.2288 to expand the existing Section 45Q CO_2 tax credits, which are currently capped at 75 million metric tons of CO_2 (*44*). Allocation of the new credits would be classified by CO_2 source type, with separate categories for electric power, lower-cost and higher-cost industrial projects. The additional revenue generated from increased oil production would pay for the credits in ten years (*45*). Allowing CCS projects to secure tax credits in advance would also offer more financial certainty for investors. By passing an updated version of this bill that takes into account lifecycle CO_2 emissions, Congress can support CCS while generating net federal revenue in ten years (*45*).

Consider establishing a regulatory framework for CO_2 storage liability during the demonstration phase in which the federal government assumes liability after site closure and government certification.

Many private sector stakeholders perceive an unacceptably high level of risk in taking on CO_2 storage liability. A regulatory framework is needed to ensure that the risks of demonstrating a new technology are clearly delineated and distributed equitably among project developers, financers, and government. For demonstration projects, it may be appropriate for the federal government to temporarily assume a greater share of the risk, with liability transferred to the federal government after site closure and government certification to ensure that standard procedures have been followed for CO_2 sequestration and monitoring. This approach could be revisited after the demonstration phase to evaluate whether an alternate regulatory framework would be more equitable.

Consider enacting a carbon pricing mechanism, such as a cap-and-trade or a carbon tax, and direct a portion of the revenue to commit consistent levels of spending for CCS demonstration projects.

In the short term, other policy mechanisms can be used to support CCS in the demonstration phase. A carbon pricing mechanism would offer a way to fund a portfolio of demonstration projects. At this early stage in technology development, it would be premature to pick a technological pathway, so both post-combustion and pre-combustion capture should be demonstrated to develop more accurate cost estimates. Committing consistent levels of funding for large-scale CCS demonstration projects would enable technology advancements, reduce concerns among project developers about policy uncertainty, facilitate the development of a pipeline of projects that could build upon the R&D efforts at the national labs and universities, and advance DOE's goals of cost-effective, commercial deployment of CCS by 2025.

B. FOR CONGRESS AND THE OFFICE OF FOSSIL ENERGY

Re-appropriate CCS funding from the Recovery Act that went unspent, and use it to administer a fourth round of CCPI grant funding and to allow DOE greater flexibility in supporting existing projects that have already received up-front grant funding.

While the $3.4 billion in funding for CCS appropriated through the Recovery Act was an important start, about half of these funds went unspent. These funds should be re-appropriated to solicit applications for a fourth round of CCPI projects to support large-scale CCS power plant demonstration projects. To avoid having the government "pick winners," up-front grant funding should be spread across several different projects to allow different early-stage technologies to compete. However, the Office of Fossil Energy should incorporate lessons from past projects that experienced setbacks by establishing a separate program that would competitively award and administer funds for existing demonstration projects. Given the technical and cost uncertainties associated with deploying a new technology, cost overruns should not come as a surprise. By allowing the DOE more flexibility to support projects and the discretion to increase the federal cost share, there is a higher chance that those projects will succeed.

While increased funding is difficult, two factors would make it more feasible. First, Congress has previously authorized funding for CCS that went unspent, due to technical and cost uncertainties that are to be expected for a technology in the demonstration phase. In addition, CCS has the potential to draw bipartisan support, because it has backing from both industry and environmental groups.

C. FOR STATE GOVERNMENTS

Consider low carbon portfolio standards to support the development of CCS along with other low carbon options.
A low carbon portfolio standard that mandated a certain percentage of electricity from low carbon energy sources, which would include not just fossil-fuel power plants equipped with CCS but also renewables or nuclear, would put CCS on equal footing with other low carbon energy sources. The renewable portfolio standard, which mandates that a certain percentage of electricity come from renewable energy, was instrumental to the development of the wind industry in the U.S., and a low carbon portfolio standard could prove equally critical for CCS. In addition to allowing CCS project developers to secure rate recovery for their investments, low carbon portfolio standards could allow states to comply with EPA regulations.

D. FOR CCS FINANCERS

Adopt a standardized model for quantifying the carbon storage liability risk so that it can be equitably allocated.
In order to allocate the risks posed by long-term CO_2 storage, a standardized methodology for calculating risk profiles for each storage site needs to be adopted by the project finance community. The ability of CCS financers to assess and price risk has been proven in other industries where there are low-probability, high-impact risks, such as the oil industry. A similar mechanism can be adapted for CCS. The results of one financial simulation model, which was based on standard risk assessment approaches used in the finance and insurance industries, indicated that the carbon liability risk amounted to less than 0.4 percent of the total estimated cost for a proposed CCS project (*46*).

***Develop tax equity financing strategies that allow firms to more effectively utilize carbon sequestration tax credits*.**
While tax credits are likely to be the easiest way for Congress to provide policy support for CCS, the low tax burdens of many CCS project companies means that these tax incentives are likely to have little impact. Therefore, there is an opportunity for CCS financers to develop strategies that allow CCS project companies to form partnerships with so-called tax equity investors, who do have sufficient taxable incomes and are able to utilize these tax credits (*12*).

E. FOR CCS PROJECT DEVELOPERS

Seek out creative business models that allow multiple revenue streams.
Having a diversified revenue stream reduces dependence on government subsidies and increases a project's chance of succeeding. NRG's Petra Nova CCS Project, which essentially allowed new infrastructure at an existing power plant to be paid for with additional oil production from the use of CO_2 for EOR, is an excellent example of a creative business model that offers NRG a greater return. This business model could be replicated for other fossil fuel-fired power plants near oil fields and even adapted for other cases where CO_2 can be beneficially used.

This paper was adapted from the work of Kathleen Wu, a chemical engineering graduate of Yale University, under the auspices of AIChE and the Washington Internships for Students of Engineering program.

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