CarbonSAFE: Commercialization of Emerging Environmental Sustainability Technologies: CCS Development & Implementation Policy

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CCS Development & Implementation Policy

AUTHORED BY:

DESIGN ASSURANCE SCIENCES
(A division of MudTurtle Industries, LLC, Mahomet, Illinois USA)

Dr. Douglas Brauer, Principal of DAS, President & Managing Partner of MTI

2018

(The CarbonSAFE (Storage Assurance and Facility Enterprise) Project is sponsored by the U.S. Department of Energy, National Energy Technology Laboratory)

Design Assurance Sciences, 808 N. Woodspring Dr., Mahomet Illinois USA

Foreword

This report was prepared by Design Assurance Sciences—MudTurtle Industries, LLC for the Illinois State Geological Survey Division of the University of Illinois at Urbana-Champaign under UI PO# P15500704, UI CN-00033127. This work was directed by Dr. Douglas Brauer, Principal of Design Assurance Sciences and President & Managing Partner of MudTurtle Industries, LLC. Additionally, Cheston Brauer, Director of Strategy Implementation, Rush University, Chicago, Illinois USA, provided strategic planning insights; and Dr. Roh Pin Lee, Director of "STEEP-CarbonTrans," TU Bergakademie Freiberg, Germany provided insights for societal education, outreach, and the circular carbon economy.

.The document addresses the commercialization of emerging environmental sustainability technologies and provides case study material based-on carbon capture, utilization, and sequestration (or storage) (CCUS) technology (or commonly referred to as carbon capture and storage, CCS). It was developed as part of the U.S. Department of Energy, National Energy Technology Laboratory Project "CarbonSAFE" being conducted by the Prairie Research Institute--Illinois State Geological Survey Division, at the University of Illinois at Urbana-Champaign.

This report contributes to the overall project ***Task 5.0 – Permitting and Compliance; Subtask 5.1 – Policy, Regulatory, Legal and Permitting Case Study.*** For this subtask, CCS business development assessment information was assembled to assist in identifying local, state, and national regulatory and policy positions impacting the establishment of a CCS storage complex.

Tasked issues addressed within this report include:

- ✓ Information on assessment of US and Illinois governmental policy regarding CCS viability and sustainability

The decision to invest in emerging environmental sustainability technologies requires an understanding of the return-on-investment risks. Numerous variables provide challenges for emerging CCUS/CCS technologies including technological, financial, governmental policy, storage potential and permanence, and public/societal acceptance. To promote dialogue regarding the issues impacting this emerging technology, this report provides insights into stakeholder obstacles that may impact the decision to invest in CCS technologies and to bring them through technology transfer and into commercialization.

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EXECUTIVE SUMMARY

The topic of carbon capture, utilization, and sequestration (or storage) developed out of concerns for the increasing levels of carbon dioxide (CO_2) in our atmosphere leading to changes in the Earth's environment. Specifically, these concerns regard an accelerated increase in CO_2 causing climate change seen as Earth's global warming.

Researchers have linked climate change to the increased use of fossil fuels as a result of rapid technology advancement since the industrial revolution. The 4th assessment report of Intergovernmental Panel on Climate Change (IPCC) in 2007 forecasted that the global warming was caused by greenhouse gas (GHG) such as CO_2 and methane (CH_4) gas as a result of human activity and that the world will be confronted with a serious crisis without a dramatic reduction effort of GHGs (IPCC, 2007).

Fast forward to the 2014, and the conclusion remained that anthropogenic GHG emissions (i.e., carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O)) have increased since the pre-industrial era, driven largely by economic and population growth (IPCC, (2014). With this position, anthropogenic effects are the catalyst that has led to unprecedented atmospheric concentrations of CO_2, CH_4, and N_2O in over 800,000 years. Their effects, together with those of other anthropogenic drivers, have been detected throughout the climate system and labeled "*extremely likely"* to have been the dominant cause of the observed warming since the mid-20th century (IPCC 2014).

Considering the IPCC's early forecast on the relationship of climate change with greenhouse gas in atmosphere and the continued global consumption of fossil fuels, the International Energy Agency (IEA) suggested the need for global policy for one to provide the pathway to mitigating climate change due to GHGs. This pathway references a reduction of CO_2 emission by 50% of the 2005 emission amount by 2050 (IEA, 2008). This would require global policy leading to an annual 48 billion-ton reduction of CO_2 released to the atmosphere.

Anthropogenic GHG emissions are mainly driven by population size, economic activity, lifestyle, energy use, land use patterns, technology and climate policy. It is suggested that between 1750 and 2011, that approximately 40% of the cumulative anthropogenic CO_2 emissions to the atmosphere have remained in the atmosphere (IPCC, 2014); the rest was removed from the atmosphere and stored on land (in plants and soils) and in the ocean. The ocean has absorbed about 30% of the emitted anthropogenic CO_2, which is discovered to be causing ocean acidification (IPCC, 2014).

While terrestrial CCS is a valued, and natural, reduction mechanism, there is the need for global policy that facilitates societal-embraceable technologies for effective and safe reduction of GHGs and, particularly, CO_2. One technological pathway to achieve reduction targets is CCUS. The IEA predicts that energy efficiency contributes 24%, renewable energy contributes 21% and that CCUS contributes to 19% of global carbon dioxide mitigation by 2050 (Huha, Parka, Yooa & Hwanga, 2011).

This report is designed to serve as a tool for local, national, and global policy discussions. The focus in on CCUS technologies and includes a CCUS industry overview, a discussion of CCUS technology commercialization challenges and opportunities, and a review of policy initiatives.

CCUS INDUSTRY OVERVIEW

Carbon capture, utilization and sequestration (or storage) (CCUS) involves capturing man-made (i.e., anthropogenic) carbon dioxide (CO_2) at its source and storing it, or utilizing it for tangential product manufacture, to avoid its release to the atmosphere. While CCUS reflects the concept of using the captured CO_2 for production purposes (e.g., coatings, lubricants, and enhanced oil recovery (EOR)), the overall process is commonly shortened to CCS. The important fact is that CCS reduces the amount of CO_2 released to the atmosphere (e.g., from the burning of fossil fuels at power plants) (IPCC, 2013). Fundamentally, the CCS process, when the CO_2 is not being utilized for synthetic daily-use products, includes three main steps: (1) capturing and separating CO_2 from other gases; (2) purifying, compressing, and transporting the captured CO_2 to the storage site; and (3) injecting the CO_2 into underground geological reservoirs (Folger, 2017).

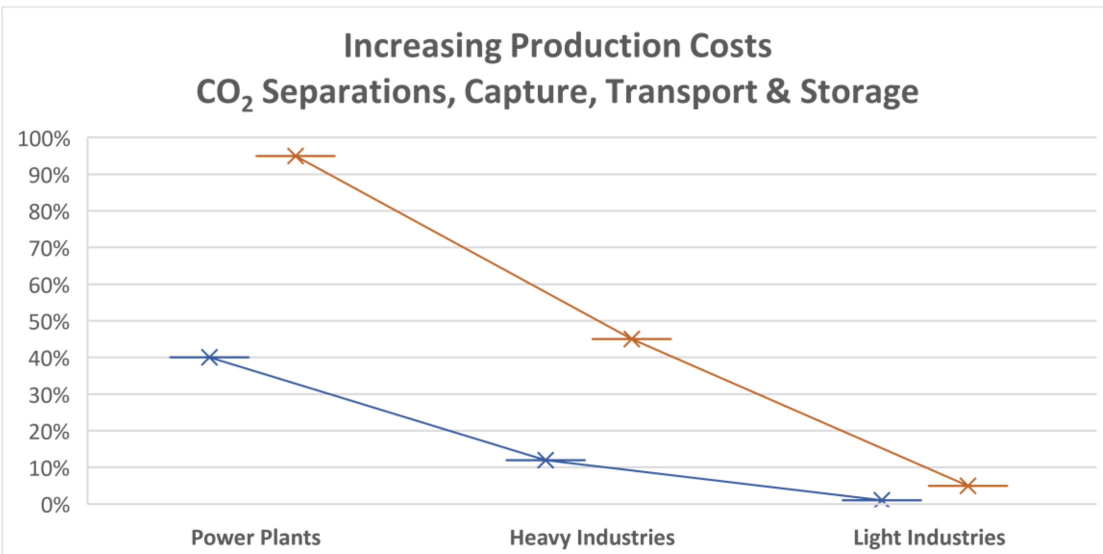


Figure 1 Increase in Costs for Energy Production using CCS Technology (Soupa & Lojoie, 2012)

While CCS technologies continue to develop, a significant limiting commercialization barrier is their cost, and the passage of that cost to the customer. Figure 1 (Soupa & Lojoie, 2012) provides an overview of relative increase in costs for power plants (40% to 95%), heavy industries (12% to 45%), and light industries (1% to 5%) emitting highly pure CO_2 (e.g., ethanol production facilities). It is clear that the greater the CO_2 removal needed, the greater the production costs that will be absorbed by end-user consumer. For any emerging technology there is an expected return-on-investment (ROI) within a defined timeframe. The inability to achieve this ROI is the point at which the technologies' commercialization potential is critically wounded, particularly, in the private sector. That is, the costs passible to the end consumer reach a point of unacceptability, and thereby severely impact the profit potential.

With increasingly greater competition for governmental funding, sponsored research is increasingly more difficult to justify from a purely financial ROI perspective (Brauer, 2014). This is the challenge for the U.S. Department of Energy (USDOE), which has long supported research and development of emerging CCS technologies as part of its Fossil Energy Research and Development activities. Of course, the liveliness of large-scale technology development investments is often at the mercy of the current governmental administration holding power.

While CCS technologies received strong support during the Bush and Obama Administrations in the United States, the same technology endorsement is not present with the current Trump Administration. The current Administration cut Federal CCS technology development funding substantially in its FY2018 budget proposal request.

The Trump Administration's proposal differs from the policy trends of the previous two Administrations. Those Administrations supported R&D on CCS and emphasized the development of large-scale demonstration projects. That support facilitated new commercialization ventures using technologies developed at the pilot, or proof-of-concept, scale that were ramped up to commercial demonstration scale (Folger, 2017). The current Administration's curtailed funding for CCS, coupled with the successful launch of one large CCS plant in January 2017 (the Petra Nova plant in Texas) and the suspension of another in June 2017 (the Kemper County Energy Facility in Mississippi), has create much uncertainty about the future of CCS (and CCUS). This movement of USDOE sponsorship focus on laboratory R&D and away from demonstration will likely increase the lag of emerging CCUS technologies from R&D to commercialization. As illustrated in Figures 2 and 3, Soupa and Lojoie (2012) raised awareness of the general lack of technologies moving into the commercialization phase of technology transfer.

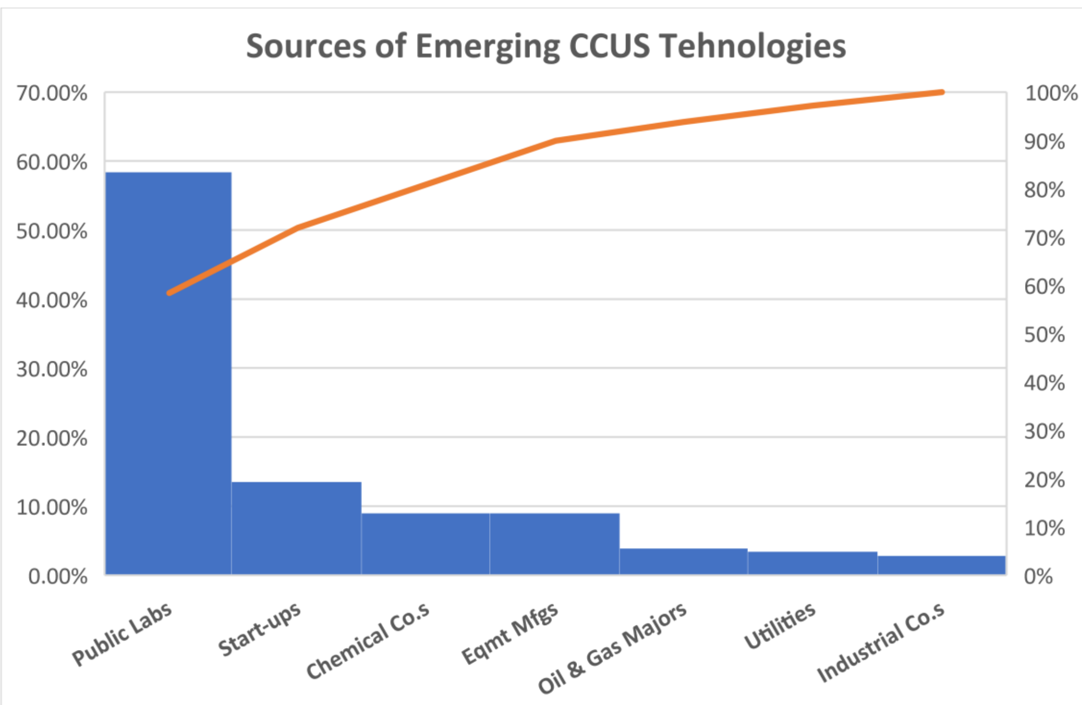


Figure 2 Sources of CCUS Emerging Technologies (Soupa & Lojoie, 2012)

While research laboratories will undoubtedly remain a significant source of technology developments, the lack of industry participants doing self-funded "in house" research, creates broad concerns regarding industry commitment to driving technology transfer and commercialization, with or without governmental co-funding.

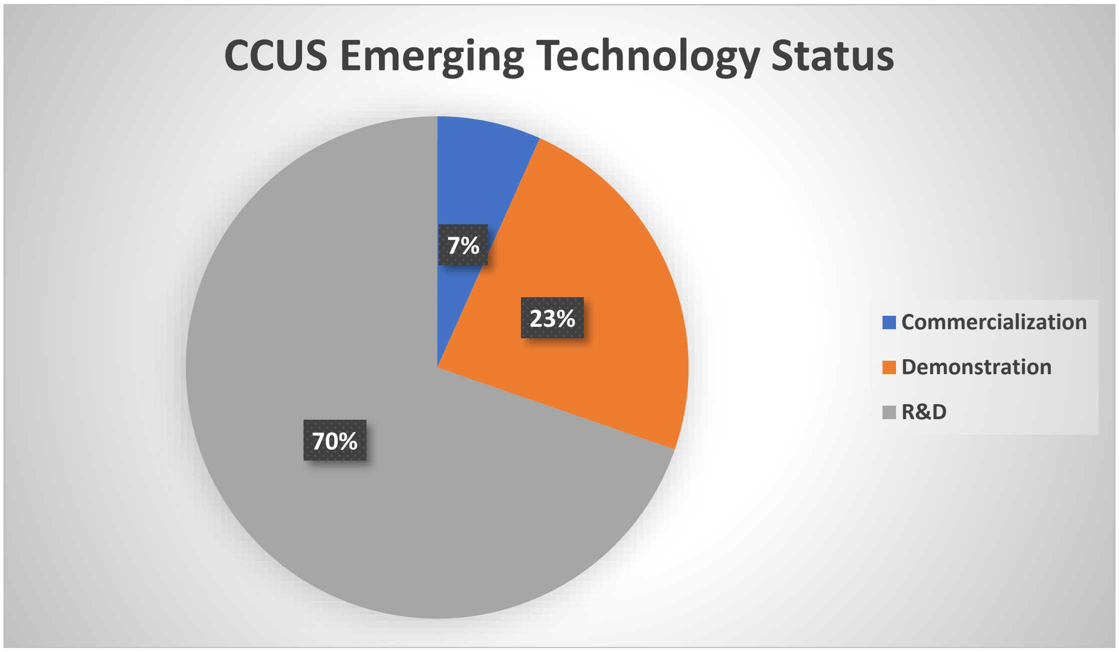


Figure 3 Business Development Status CCUS Emerging Technologies (Soupa & Lojoie, 2012)

CLIMATE CHANGE & TECHNOLOGY

The increase in global population has increased access to, and demand for, economic advancement typically linked to energy consumption. This has resulted in the rapid increase in anthropogenic GHG emissions, particularly, that resulting from an increase in the use of fuels to produce energy (i.e., coal, oil, and natural gas). Society's abundant use of fossil fuels has become a cause of concern due to their adverse effects on the environment, particularly related to the emission of CO_2.

According to the Emission Database for Global Atmospheric Research (EDGAR, 2011), global emission of CO_2 was 33.4 billion tonnes (metric) in 2011, which was 48% more than that of the two previous decades. Over the past century, the atmospheric CO_2 level has increased more than 39%, from 280 ppm during pre-industrial time (IPCC, 2007) to the record high level of 400 ppm in 2013 with a corresponding increase in global surface temperature of about 0.81^0C (NOAA, 2013). The Intergovernmental Panel on Climate Change (IPCC) forecasted that by 2030 global GHG emissions would will increase by 25 to 90% over the year 2000 level, with CO_2-

equivalent concentrations in the atmosphere growing to as much as 600–1550 ppm (IPCC, 2007c).

The IPCC 5th Assessment Report (AR5) confirmed the IPCC 4th Assessment Report's assertion that global warming of our climate system is unequivocal and is associated with the observed increase in anthropogenic greenhouse gas concentrations (NOAA, 2013; IPCC, 2013). Figure 4 (NOAA, 2018) highlights recent global climate change anomalies. The IPCC (IPCC, 2013) references that the period of 1983–2012 was likely the warmest 30 years period of the last 1400 years in the Northern Hemisphere. To avoid the worst effects of climate change occurring, it is recommended to necessarily keep the temperature rise less than 21°C relative to preindustrial levels and to reduce CO_2 emissions globally by 41–72% by 2050 and by 78–118% by 2100 with respect to 2010 levels (IPCC, 2013; Peterson & Vose, 1997; Huang, Banzon, Freeman, Lawrimore, Liu, Peterson, Smith, Thorne, Woodruff & Zhang, 2016).

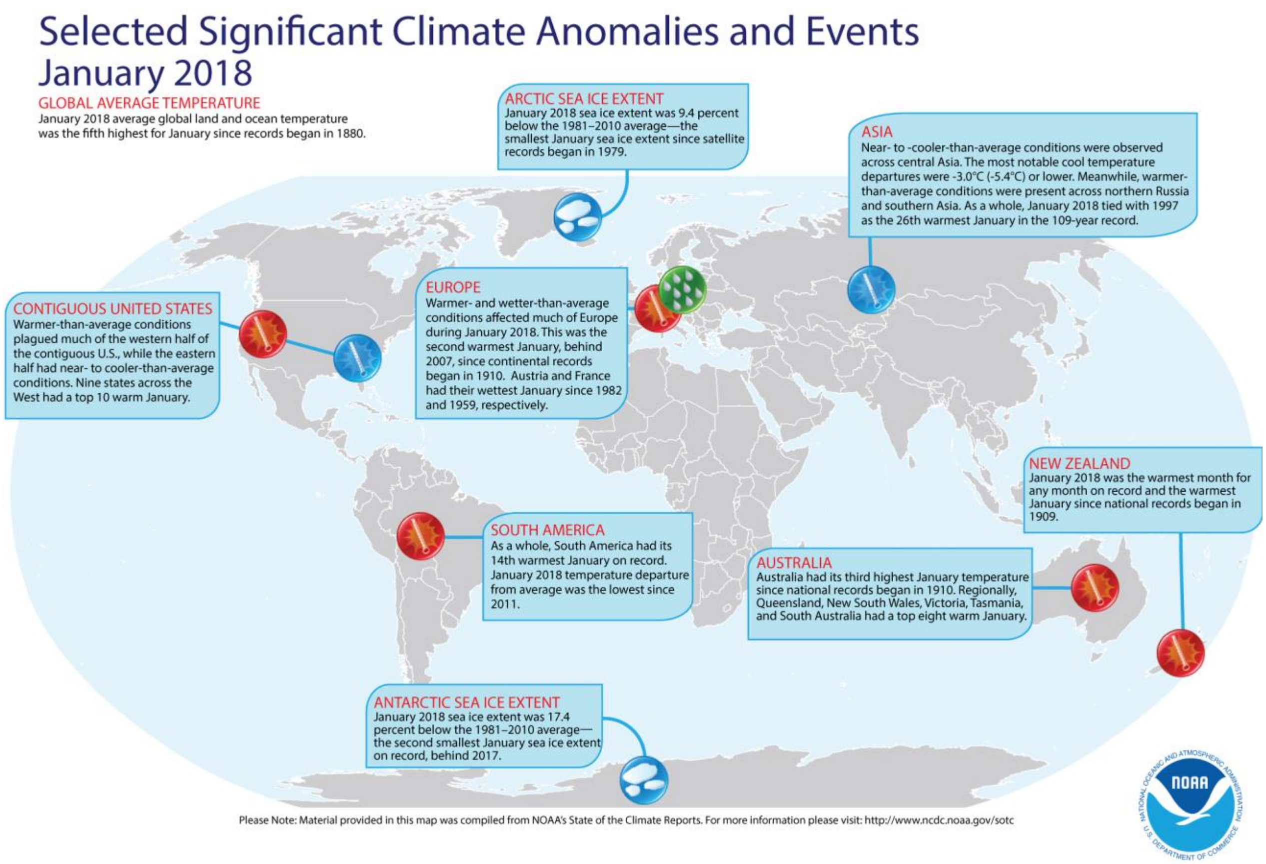


Figure 4 Significant Climate Events and Anomalies (NOAA, 2018)

Establishing global consensus for CO_2 emission control continues to be difficult. For example, at the 2013 United Nations Climate Change Conference (COP19), participating countries unanimously looked forward to a green economy leading to sustainable development. At the 2017 UN Climate Change Conference (COP23), participating countries agreed to

accelerate and complete their work to put in place climate change guidelines, officially known as the Paris Agreement Work Programme, at COP24 in 2018 (UN News, 2018). In parallel, the IPCC has continued to conduct comprehensive reviews on various CCS technologies providing a valuable reference for researchers and policymakers in developing their GHG emission reduction programs (IPCC, 2005; IPCC, 2013)

Not surprisingly, there remains a lack of global consensus and action to mitigate the release of anthropogenic GHG, specifically $C0_2$. Moving forward in developing regional, national, and global policy, it is necessary to provide a holistic inclusion of emerging CCUS technologies, which includes CO_2 capture, separation, transport, utilization, storage, lifecycle GHG assessment, and leakage and monitoring.

As recent as 2018, the United Nations reiterated that the world is witnessing the severe impacts of climate change. Executive Secretary of UN Climate Change, Patricia Espinosa, provided three priorities for addressing climate change (UN News, 2018):

1. All stakeholders - including governments, non-governmental organizations, businesses, investors and citizens – must accelerate climate action by 2020.
2. The international community must complete the Paris Agreement guidelines, or operating manual, to unleash the potential of the accord.
3. Conditions must be improved to enable countries to be more ambitious in determining their own national policies to slow down global warming.

Different approaches are considered and adopted by various countries to reduce their CO_2 emissions, including:

- Improve energy efficiency and promote energy conservation;
- Increase usage of low carbon fuels, including natural gas, hydrogen, or nuclear power;
- Deploy renewable energy, such as solar, wind, hydro power, and bioenergy;
- Apply geo-engineering approaches (e.g., off shore station and reforestation); and
- CO_2 capture, utilization, and storage (CCS/CCUS).

Table1 compares the application areas, advantages and limitations of these different approaches. Some of the approaches address source emissions reduction (i.e., clean fuels, clean coal technologies) and some address demand-side management (i.e., energy conservation) (Leung, Caramanna & Maroto-Valer, 2014). Adopting a single approach or strategy is not expected to adequately meet the IPCC goal of CO_2 reduction (i.e., 50–85% by 2050 from 2000 levels), (IPCC, 2014; 2013). Therefore, a complimentary portfolio of CO_2 emission reduction strategies needs to be developed and implemented.

Table1 Summary of CO_2 Reduction Strategies (Leung, Caramanna & Maroto-Valer, 2014)

Strategy	Application area/sector	Advantages	Limitations
Enhance energy efficiency and energy conservation.	Applied mainly in commercial and industrial buildings.	Energy saving from 10% to 20% easily achievable.	May involve extensive capital investment for installation of energy saving device.
Increase usage of clean fuels.	Substitution of coal by natural gas for power generation	Natural gas emits 40–50% less CO_2 than coal due to its lower carbon content and higher combustion efficiency; cleaner exhaust gas (lower particulates and sulfur dioxide emissions).	Higher fuel cost for conventional natural gas. Comparable cost for shale gas.
Adopt clean-coal technologies.	Integrated gasification combined cycle (IGCC), pressurized fluidized bed combustor (PFBC) etc. to replace conventional combustion	Allow the use of coal with lower emissions of air pollutants.	Significant investment needed to rollout technologies widely.
Use of renewable energy than conventional energy.	Hydro, solar (thermal), wind power, and biofuels highly developed.	Use of local natural resources; no or low greenhouse and toxic gas emissions.	Applicability may depend on local resources availability and cost. Power from solar, wind, marine etc. are intermittent and associated technologies are not mature; most current renewable energies are more costly.
Development of nuclear power.	Nuclear fission adopted mainly in US, France, Japan, Russia and China. Nuclear fusion still in research and development.	No air pollutant and greenhouse gas emissions.	Usage is controversial; development of world's nuclear power is hindered due to the Fukushima Nuclear Accident in 2011, e.g., Germany will phase out all its nuclear power by 2022.
Afforestation and reforestation.	Applicable to all countries.	Simple approach to create natural and sustainable CO_2 sinks.	Restricts/prevents land use for other applications.
Carbon capture and storage.	Applicable to large CO_2 point emission sources	It can reduce vast amount of CO_2 with capture efficiency 480%.	CCS full chain technologies not proven at full commercial scale.

Amongst the different approaches presented in Table 1 (Leung et al., 2014), CCS can reduce CO_2 emissions (typically 85–90%) from large point emission sources, such as power production utilities, and energy intensive emitters (e.g., cement kiln plants). With a CCS approach, CO_2 is first captured from the flue/fuel gases, separated from the sorbent, transported, and then either stored permanently, or re-utilized for consumer and industrial

product applications. Additionally, CCS includes a portfolio of technologies, involving different processes for CO_2 capture, separation, transport, storage, and monitoring (Leung, et al., 2014).

As with all technology development and implementation, until the technology is demonstrated for commercial-scale application it will not advance into technology transfer and commercialization (Brauer, Lee & Brauer, 2018; Brauer & Cesarone, 1992; Brauer, 2014). As depicted in Figure 5, such is the current state for CCS in the power sector as it has not been comprehensively demonstrated at commercial-scale. Therefore, technological risks, which enhance the already significant ROI cost barrier, provide a real near-term barrier to implementation (de Coninck et al., 2009).

A lack of funding for the large-scale demonstration of technologies is a well-recognized problem in technology innovation. After a successful R&D phase, public funding is often reduced, while private funding for application of the technology is still seen as uneconomical or too risky. The cash flow for the new technology dries up, and the ensuing “valley of death” looms (Murphy and Edwards, 2003). This pattern of difficulty at the demonstration phase is common for many technologies, but is particularly pronounced in large-scale, capital intensive technologies such as CCS (de Coninck, et al. 2009).

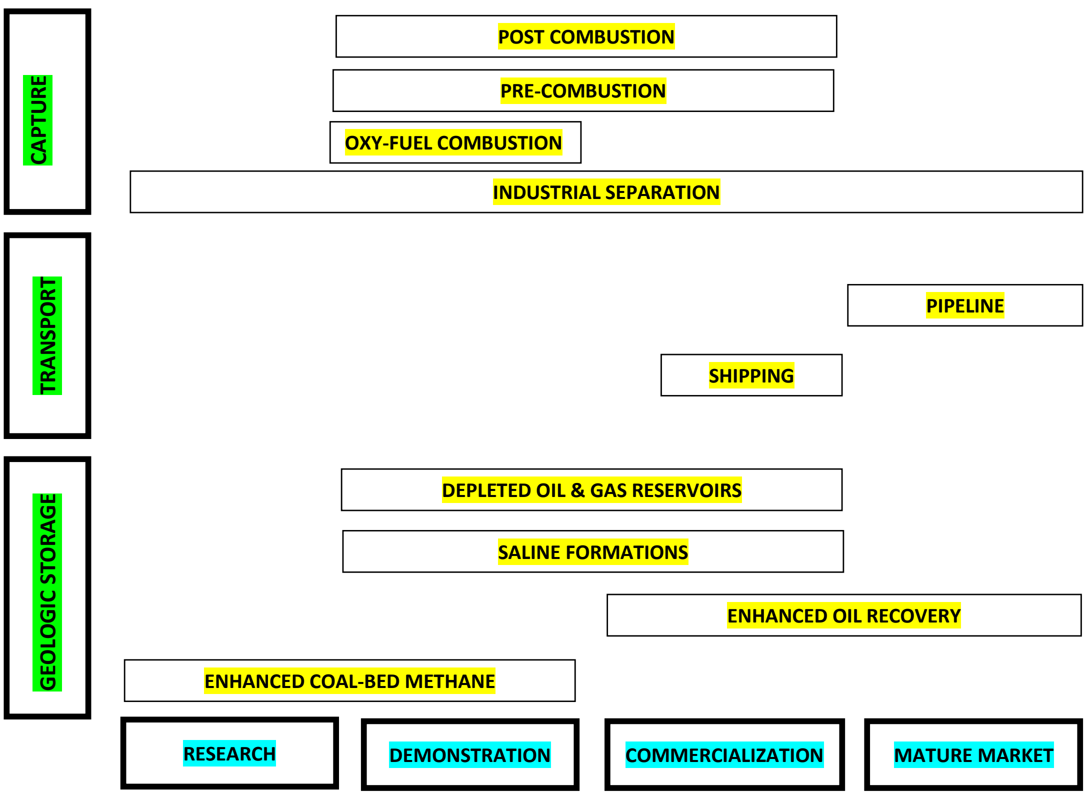


Figure 5 Stages of Maturity of CCS Components (de Coninck, Stephens & Metz, 2009)

Most global emission projections continue to suggest that large-scale implementation of CCS is required to achieve deep reductions in emissions within the next few decades (IPCC,

2014). In Figure 6, the SBC Energy Institute (Soupa, Lajoie, Long & Alvarex, 2012) illustrated the stages of CCS development projected into the future. Advocates highlighting the need for ongoing CCUS development have been vocal for many years. The IEA World Energy Outlook (2008), for example, showed that significant CCS deployment is needed from years 2020 to 2030 to achieve a 450 ppm instead of a 550 ppm emission stabilization scenario.

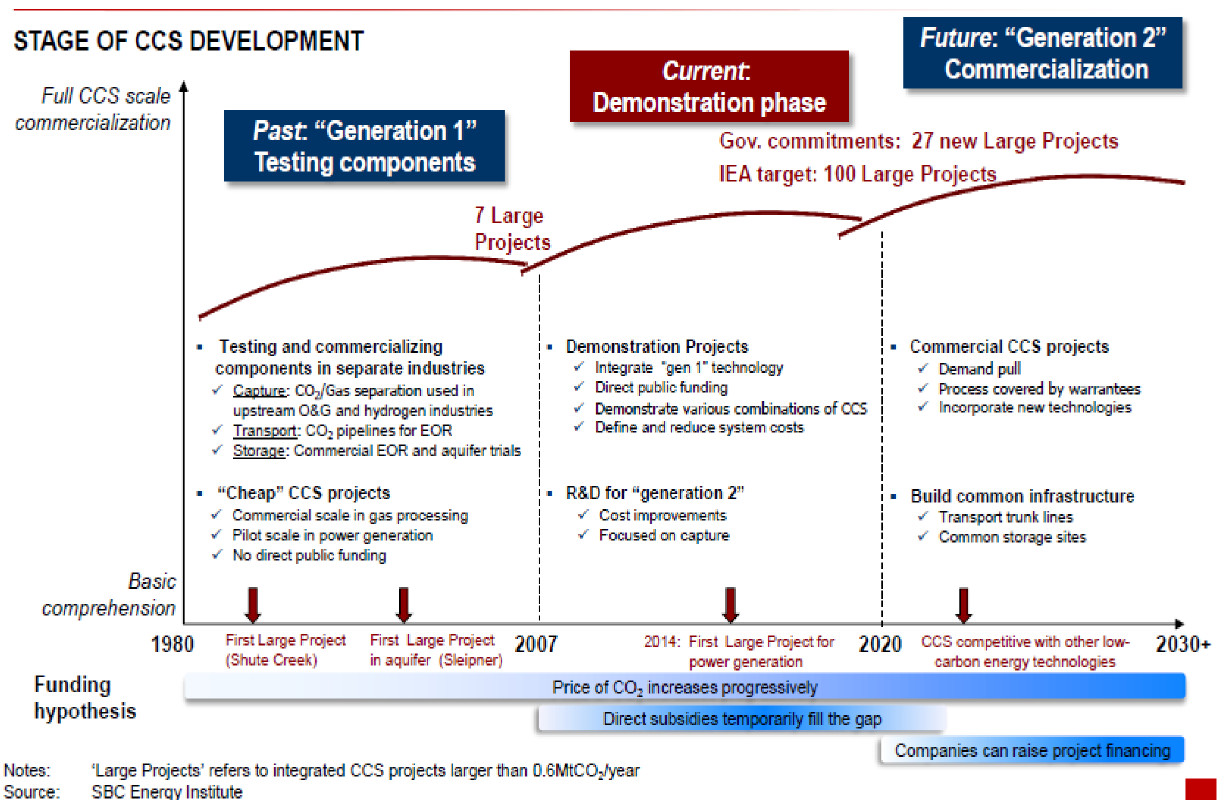


Figure 6 Stages of CCS Development (Soupa, Lajoie, Long & Alvarex, 2012)

As CCS commercial-scale demonstration remains financially challenged (Hughes, 2017), various GHG accounting frameworks have developed methodologies to document and quantify emissions reductions strategies that can financially support using CCS technology implementation (e.g., carbon offset credits). In 2012 (DNV, 2012), a certification framework for CCS projects was launched. Nationally, in the United States, the Center for Climate and Energy Solutions issued a "GHG Accounting Framework for Carbon Capture and Storage Projects" to guide CCS project developers and advance policies that reward qualified CCS investments (McCormick, 2012).

At the State level, California investigated the inclusion of CCS in California's climate law, AB 32, which would enable CCS to quality for carbon offset credits (California CCS Review Panel, 2010). The availability of financial incentives, no doubt, could facilitate CCS technology transfer and commercialization.

As a model for other States, the State of California Air Resources Board is currently developing a quantification methodology for CCS (CA ARB, 2018). As with other quantification methodologies, the CCS quantification methodology may be adopted for use in the Cap-and-Trade and Low Carbon Fuel Standard programs as determined appropriate in rulemaking(s) specific to these programs (CA ARB, 2018). Studies by the Intergovernmental Panel on Climate Change (IPCC, 2005) and the California Council on Science and Technology (CCST, 2015), have re-affirmed that CCS has the potential to reduce carbon emissions by millions of metric tons, and may be an integral part of meeting California's long term climate goals. The State of California has been a leader in advocating that CCS allows for existing fossil resources, such as natural gas, to be used in a way that is much lower in carbon emissions than traditional methods.

In the United States at the Federal level, the Obama Administration commissioned a CCS task force in 2010, which concluded that the largest barrier to long-term demonstration and deployment of CCS technology is the absence of a Federal policy to reduce GHG emissions. The task force further concluded that widespread deployment of CCS would occur only if the technology is commercially available at economically competitive prices. Folger (2017) stated that at present none of those factors appear to be in place, which may indicate that demonstration and deployment of industrial commercial-scale CCS will be delayed pending future policy, technological, and economic developments.

Historically, the USDOE has funded R&D for an integrated CCS system since 1997. Since FY2010, the U.S. Congress has provided more than $4.3 billion in annual appropriations for CCS activities at DOE. The Recovery Act provided an additional $3.4 billion to that total Folger (2015).

GLOBAL PROJECTS

The Global CCS Institute highlights that CCS is proven and highly versatile. It has been applied in a wide range of industries since 1972 when several natural-gas processing plants in the Val Verde area of Texas began employing carbon capture to supply CO_2 for EOR operations (GCCS, 2017). Since then, over 200 million tonnes of CO_2 has been captured and injected into underground geological structures. Early application of CCS technologies in the 1970s and 1980s involved processes in which CO_2 was already routinely separated, such as in natural gas processing and fertilizer production. This was then augmented with the demand for CO_2 for use in EOR. Today, the portfolio of CCS facilities is much more diverse, including applications in coal-fired power, steel manufacture, chemical, and hydrogen production, and bio-energy.

While CO_2-EOR remains a key business driver for CCS, wider geological storage solutions are now represented among operating projects. Much has been achieved over the last four decades (GCCSI, 2017):

- Capture technologies are widely employed at scale globally, and costs are falling. rapidly as new facilities come onstream and next generation technologies are unleashed
- More than 6,000 kilometers (km) of CO_2 pipelines are operational with an excellent safety record.
- CO_2 is injected securely into a variety of strata with no evidence of leakage to the atmosphere.

Figure 7 (GCCSI, 2017) highlights the ongoing global CCS project application industries and countries. There are seventeen large-scale CCS facilities in operation globally, capturing more than 30 MTPA (million tonnes per annum) of CO_2. Additionally, four large-scale facilities are currently in construction, all planned to be operational in 2018, and capable of capturing an additional six MTPA of CO_2. In 2017, there were recorded fifteen smaller scale CCS facilities in operation or under construction around the world. The CO_2 capture capacity of these individual facilities ranges from around 50,000 to almost 400,000 TPA. In total, these facilities can capture over 2 MTPA of CO_2. All this carbon capture capacity adds up to the equivalent of over 8 million motor vehicles taken off the roads.

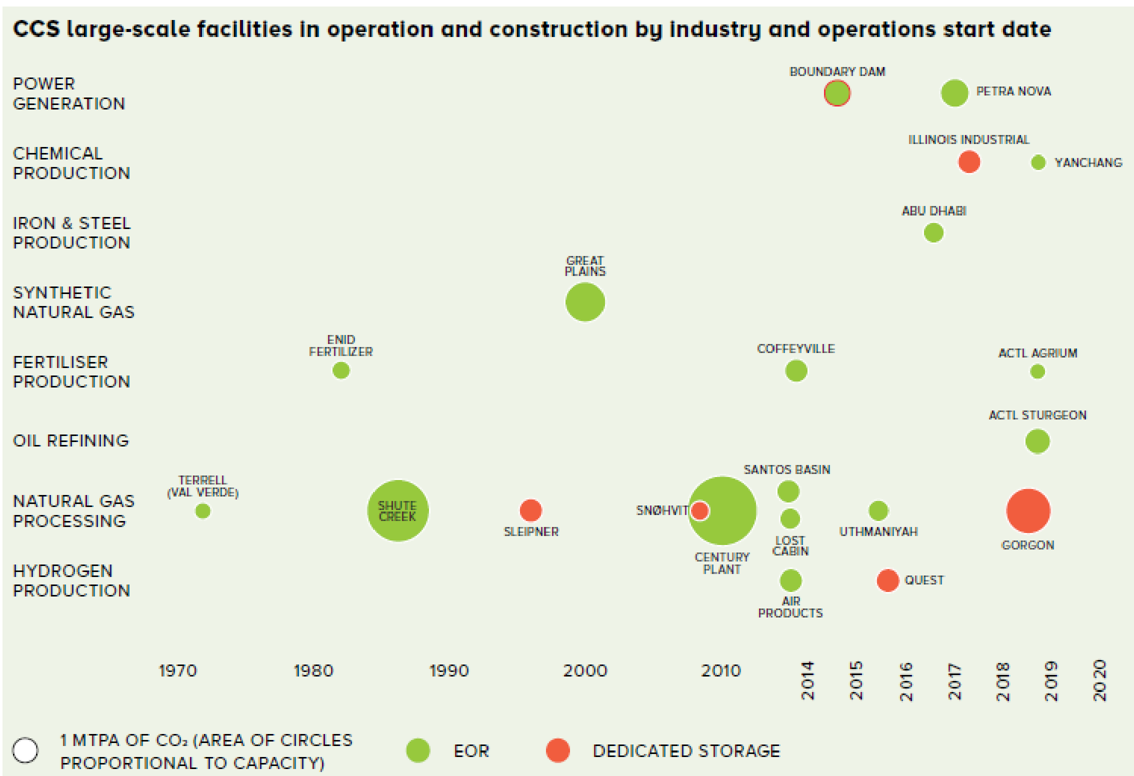


Figure 7 Global CCUS Projects (GCCSI, 2017)

Coal-Fired Power Plants

Globally, two fossil-fueled power plants currently generate electricity and capture CO_2 in large quantities: 1) Boundary Dam plant in Canada and 2) Petra Nova plant. Both plants retrofitted post-combustion capture technology to units of existing plants. A third fossil-fueled electricity-generating operation, the Kemper County Energy Facility, was scheduled to begin CCS operations by now, but cost overruns and delays in construction and operations led to the suspension of the plant's CCS component in June 2017 (USDOE, 2017). Unlike the two retrofitted plants, Kemper was built from scratch with a pre-combustion integrated gasification combined cycle (IGCC) system. Other types of plants use CO_2 capture technology as part of their

industrial process, such as the Great Plains Synfuels Plant or in some natural gas processing plants, which need to remove the CO_2 as an impurity from the natural gas prior to shipping.

Petra Nova Project

The Petra Nova–W.A. Parish Generating Station is an industrial-scale coal-fired electricity generating plant with CCS to operate in the United States. In 2017, the plant began capturing approximately 5,000 metric tons of CO_2 per day from its 240-megawatt-equivalent slipstream using post-combustion capture technology (NRG Energy, 2017). The capture technology is approximately 90% efficient (i.e., it captures about 90% of the CO_2 in the exhaust gas after the coal is burned to generate electricity) and is projected to capture between 1.4 MTPA and 1.6 MTPA tonnes of CO_2 each year (Marshal & Klump, 2017). The captured CO_2 is transported via an 82-mile pipeline to the West Ranch oil field, where it is injected for EOR. NRG Energy, Inc., and JX Nippon Oil & Gas Exploration Corporation, the joint owners of the Petra Nova project, together with Hilcorp Energy Company (which handles the injection and EOR), expect to increase West Ranch oil production from 300 barrels per day before EOR to 15,000 barrels per day after EOR (NRG Energy, 2017).

The USDOE provided Petra Nova with more than $160 million from its Clean Coal Power Initiative (CCPI) Round 3 funding, using funds appropriated under the American Recovery and Reinvestment Act (AARA) of 2009 (Recovery Act; P.L. 111-5) together with other USDOE Federal research and development funding for a total of more than $190 million of federal funds for the $1 billion retrofit project (USDOE, 2017).

The Petra Nova is the only CCPI Round 3 project that expended its ARRA funding and is currently Operating (Folger, 2017). The three other CCPI Round 3 demonstration projects funded using AARA appropriations, as well as the FutureGen 2.0 project, which was to receive nearly $1 billion in AARA appropriations, have all been canceled, suspended, or remain in development (Folger, 2017). The Petra Nova plant is projected to capture more CO_2 per year than the other currently operating power plant with CCS, Canada's Boundary Dam, which captures about 1 MTPA. Petra Nova also generates more electricity than Boundary Dam, about 240 megawatts compared to Boundary Dam's 115 megawatts. Both projects retrofitted one unit of much larger multi-unit electricity generating plants. The Petra Nova project retrofitted Unit 8 of the W.A. Parish power plant, which in total consists of four coal-fired units and six gas-fired units, comprising more than 3.7 gigawatts of gross capacity, making it one of the largest U.S. power plants (Parish, 2015).

In 2015, the entire W.A. Parish complex emitted nearly 15 million tons of CO_2 from all of its generating units (Parish, 2015). The Petra Nova project reduces CO_2 emissions overall from the entire complex by about 11%. By comparison, in 2015, total U.S. CO_2 emissions from the electricity-generating sector were about 1.9 billion tons (USEPA, 2017). The Petra Nova project would reduce that total by a small percentage (approximately 0.08%). However, according to DOE, a purpose of Petra Nova was to demonstrate that post-combustion capture and reuse can be done economically for existing plants when there is an opportunity to recover oil from nearby oilfields. The Petra Nova has the potential to enhance the long-term viability and sustainability of coal-fueled power plants across the United States and throughout the world (USDOE, 2017).

Petra Nova first captured CO_2 in September 2016 and has delivered more than 100,000 tons of captured CO_2 to the West Ranch Oil Field through an 80-mile pipeline. Final performance

acceptance testing on the facility was completed in December 2016 and the facility turned over for operations. During performance testing, the system met all performance criteria including capturing more than 90% of CO_2 from a 240 MW equivalent slipstream of flue gas off an existing coal-fueled electrical generating unit at the WA Parish power plant in Fort Bend County, southwest of Houston (USEPA, 2017; USDOE, 2017). At this level of operation, Petra Nova can capture more than 5,000 tons of CO_2 per day, which is the equivalent of taking more than 350,000 cars off the road.

Hilcorp Energy Company operates the West Ranch Oil Field and uses the Petra Nova captured CO_2 to boost production for EOR at the West Ranch Oil Field, jointly owned by NRG, JX Nippon and Hilcorp. Together, Hilcorp and the University of Texas-Bureau of Economic Geology monitor the movement of CO_2 deep in the oil reservoir. Oil production at the field is estimated to increase from approximately 300 barrels per day (pre-EOR) to production of up to 15,000 barrels per day (with CO_2-EOR) (NRG Energy, 2017).

Petra Nova is a joint venture by NRG and JX Nippon. Additionally, the USDOE committed to provide up to $190 million in grants as part of the Clean Coal Power Initiative Program (CCPI), a cost-shared collaboration between the Federal government and private industry. A portion of the project was financed with project loans from the Japan Bank for International Cooperation (JBIC) and Mizuho Bank, backed by Nippon Export and Investment Insurance (NEXI) (NRG Energy, 2017; USDOE, 2017).

Petra Nova uses a process jointly developed by Mitsubishi Heavy Industries, Ltd. and the Kansai Electric Power Co., Inc., which employs proprietary solvent for the CO_2 absorption and desorption. Sixteen-foot diameter ductwork takes flue gas from the coal plant to the carbon caption facility where the CO_2 is removed from the flue gas by the amine solution in the tall absorption tower and then separated from the amine as 99.9% pure CO_2 in the smaller regenerator tower to the right before being compressed and delivered to the oil field. The carbon capture facility was constructed under a fixed-price contract by a consortium of Mitsubishi Heavy Industries Americas, Inc. and The Industrial Company (NRG Energy, 2017).

By being integrated into an existing coal-burning energy plan, the Petra Nova project illustrates the economic feasibility to demonstrate the CCS technology commercialization. This project provides a roadmap for economically making existing and new fossil fuel plants significantly more environmentally friendly.

Kemper Project

In June 2017, Southern Company and its subsidiary Mississippi Power announced they were suspending the start-up of the coal gasification component of their Kemper County Energy Facility (Southern Company, 2017), a pre-combustion technology that would combine IGCC with CCS to capture CO_2 and transport the gas for EOR at a nearby oilfield. The suspension of operations comes after several years of cost overruns and delays. That is, total costs escalated to more than $7 billion from approximately $2.67 billion and the original target start-up date in 2014 was missed (Perez, 2017). The plant will continue to generate electricity from burning natural gas, according to Southern Company, pending a decision from the Mississippi Public Service Commission on future operations (Southern Company, 2017).

The USDOE supported the Kemper County plant with a $270 million award for the development and deployment of a gasification technology called Transport Integrated

Gasification, under a cooperative agreement as part of the CCPI Round 2 program. The $270 million award represented approximately 10% of what USDOE had reported as the overall cost to build the plant, approximately $2 billion (USDOE, 2017). At the time of the award, the plant was expected to have an estimated peak net output capability of 582 megawatts and was designed to capture 65% of the total CO_2 emissions released. According to the USDOE (USDOE, 2017), that would have made the CO_2 emissions from the Kemper project comparable to emissions from a natural gas-fired combined cycle power plant.

The estimated 3 million tons of CO_2 captured each year from the plant were to be transported via pipeline for use in EOR operations at nearby depleted oil fields in Mississippi. The Mississippi Public Service Commission approved the project, subject to a cap on total costs of $2.9 billion. Construction began in 2010 (Folger, 2017). Some observers attributed the cost escalation and project delays to a combination of increased piping, materials, and labor costs due to resizing and re-scoping of the original design of the CCS component (USDOE, 2017). In addition, Kemper's status as a first-of-its-kind facility likely contributed to cost overruns and construction delays. Suspension of the Kemper County plant increases uncertainty about the future of large CCS projects at coal-fired power plants in the United States and, by extension, into the future of coal.

Kemper is not the first large, USDOE-supported CCS demonstration project to hit roadblocks leading to delay and even cancellation. The current Trump Administration did not support large CCS demonstration projects in its FY2018 budget request and proposed to substantially reduce CCS funding and refocus its entire FER&D portfolio on "early-stage" research (Folger, 2017). Suspension of the Kemper County Energy Facility signaled a deeper problem with the viability of CCS at fossil-fuel burning power plants generally (Hughes, 2017).

Boundary Dam Project

The Boundary Dam project in Canada was the first commercial-scale power plant with CCS in the world to begin operations. Boundary Dam, a Canadian venture operated by SaskPower, cost approximately $1.3 billion according to one source (MIT, 2016). Of that amount, $800 million was for building the CCS process and the remaining $500 million was for retrofitting the Boundary Dam Unit 3 coal-fired generating unit. The project also received $240 million from the Canadian federal government. Boundary Dam started operating in October 2014, after a four-year construction and retrofit of the 150-megawatt generating unit. The final project was smaller than earlier plans to build a 300-megawatt CCS plant, but that original idea may have cost as much as $3.8 billion. The larger-scale project was discontinued because of the escalating costs (MIT, 2016).

Similar to the Petra Nova project discussed above, Boundary Dam captures, transports, and sells most of its CO_2 for enhanced oil recovery, shipping 90% of the captured CO_2 via a 41-mile pipeline to the Weyburn Field. The CO_2 not sold for EOR is injected and stored about 2.1 miles underground in a deep saline aquifer at a nearby experimental injection site. By March 2017, the plant had captured almost 1.5 million metric tons of CO_2 since full-time operations began in October 2014 (GCCSI, 2018). The 115-megawatt (net) plant plans to capture at least 1 MTPA of CO_2.

Some observers contend that Boundary Dam has yet to meet its expectations for capture

efficiency, cost, and availability (Hughes, 2017). Some technical and operational issues that reduced the amount of CO_2 captured after start-up were reported in 2016, and these issues led to shortfalls in delivery of CO_2 to the utility using the gas for EOR (Austen, 2016). Some reports also indicated that the CCS system consumed approximately 45 megawatts to capture and compress the CO_2 (Austen, 2016), out of a total capacity of 150 megawatts. This is a parasitic energy load of approximately 30% if the plant is operating at capacity output (>30% if not running at capacity).

Illinois Industry Carbon Capture and Storage Project

A key commercial-scale demonstration project began in 2010; "CO_2 Capture from Biofuels Production and Storage into the Mt. Simon Sandstone." This project is also referred to as the Illinois Industry Carbon Capture and Storage (IL-ICCS) project. The project is sponsored by the USDOE National Energy Technology Laboratory and includes the Archer Daniels Midland Company (ADM), Schlumberger Carbon Services, University of Illinois at Urbana-Champaign---Illinois State Geological Survey, and Richland Community College.

With this project, the collection of up to 3,000 metric tons per day of CO_2 from the ADM ethanol plant in Decatur, Illinois is to be captured and stored geologically deep underground in a saline reservoir. The significance of this demonstration project is that at the ADM facility the CO_2 is produced as a byproduct during the processing of corn to fuel-grade ethanol, which means that what is captured is approximately 99% pure CO_2. So, no separation technologies are necessary. The project scope included the design, construction, demonstration, and integrated operation of CO_2 compression, dehydration, and injection facilities, and monitoring, verification, and accounting (MVA) of the stored CO_2.

This project is demonstrating an integrated system for collecting CO_2 from an ethanol plant and geologically sequestering it in a saline reservoir, which includes (Brauer 2015):

- Conducting required geologic site surveys, site characterization, and modeling.
- Designing, constructing, and operating a new CO_2 collection, compression, and dehydration facility capable of delivering up to 3,000 $MtCO_2$ per day to the injection site.
- Integrating the new facility with an existing 1,000 metric tons per day CO_2 compression and dehydration facility to achieve a total CO_2 injection capacity of 1 MtA.
- Designing, constructing, and operating a storage site capable of accepting up to 3,000 metric tons of CO_2 per day.
- Implementing deep subsurface and near-surface MVA of the stored CO_2.
- Developing and conducting an integrated communication, outreach, training, and education initiative.
- Demonstrating the cost advantages and economic viability of implementing CCS at ethanol production facilities.

The IL-ICCS project will sequester industrial CO_2 in the Mt. Simon Sandstone, an extensive saline reservoir in the Illinois Basin with the capacity to store billions of tonnes of CO_2 (Brauer, 2015). Saline reservoirs are layers of porous rock that are saturated with brine (a concentrated salt solution). The Mt. Simon Sandstone is a clean sedimentary rock dominated by silicate minerals and lacking significant amounts of clay minerals (which typically clog pores and

reduce porosity), resulting in highly favorable porosity and permeability features for CO_2 storage. It is a porous rock formation (10-25% pore space) at more than a mile below the surface in Central Illinois, USA.

The project is designed to demonstrate CCS at a rate of 1 million TPA, which is equivalent to the annual CO_2 emissions of more than 200,000 automobiles. Nearly 50 years of successful natural gas storage in the Mt. Simon Sandstone indicates that this saline reservoir and overlying seals will safely contain the sequestered CO_2.

The IL-ICCS project is the largest saline storage industrial-scale demonstration project under construction in the U.S. This project demonstrates a cost-effective technology for the separation and capture of CO_2 for its transport and long-term safe storage in a saline reservoir. As a successful demonstration project, it facilitates the deployment of such technologies through collaborative efforts that address important technical, economic, and environmental issues. This project will also promote awareness of carbon utilization and storage technologies through its outreach component (Brauer, 2013).

Specific project outcomes include:

- Demonstration of commercial-scale saline reservoir storage in the U.S. and cost-effective and safe processes and best practices for CCS and corresponding MVA.
- Validate the Mt. Simon Sandstone saline reservoir site for commercial-scale, long-term geologic storage of CO_2.
- Inject and permanently store up to two million metric tons of CO_2.
- Collect crucial scientific and engineering data in advance of carbon capture requirements to add to the understanding of large-scale CO_2 storage in saline formations.

Specific advantages of the project include:

- Because all of the collected CO_2 is produced from biologic fermentation, a significant feature of the IL-ICCS project is its nearly "negative carbon footprint," meaning that the storage results in a net reduction of atmospheric CO_2. Additionally:
  - The CO_2 concentration in the collected stream is already high, which enhances project economics.
  - The manufacturing process generating the CO_2 is less than 1 mile from the CO_2 injection site, thereby avoids the expense of developing a lengthy pipeline.
- Successful implementation of this project could:
  - Facilitate exploration of long-term CO_2 utilization options, such as EOR and carbonate-based chemicals production.
  - Develop a market for the CCS technology in the U.S. for some of the approximately 200 fuel grade ethanol plants that have access to geologic storage.
  - Develop a market for utilization of U.S. geologic saline storage capacity of CO_2 that is estimated to range from 1,700 to 20,000 billion tonnes.

- Demonstration of compression and dehydration technology, as well as CO_2 storage experience, is a public-benefit activity and is applicable to coal-fired power generation and other industries.

Community outreach and education activities in CCS are an integral part of the IL-ICCS project. This includes conducting an integrated communication, outreach, training, and education initiative, which engages stakeholders in understanding CCS and the IL-ICCS project (Brauer, 2014a; Brauer, 2014b). Knowledge sharing and training in CCS and related technologies are the prime objectives.

COMMERCIALIZATION ISSUES

The transition of emerging technologies to commercialization is a process populated with a multitude of barriers, which include research, development, and commercial-scale demonstration of an economically viable technology providing an acceptable ROI (Brauer & Cesarone, 1992). For both private and public projects, high investment technologies are likely to find themselves in competition for a share of limited R&D resources (Beck, 2013). Such is the case for CCS technology development, which has typically required public financial assistance to subsidize the process to arrive at a level of technology maturity and demonstration ready for commercialization.

In the 1980s, scientists (largely representing the United States) began investigating CCUS as an important technology solution in a portfolio of power-generation options (e.g., renewable energy, nuclear power, and environmental awareness and conservation) to mitigate global climate change, largely caused by anthropogenic causes, including the burning of coal for power generation. Embracing CCUS looked to provide potential global solutions, particularly, for the United States, to mitigate GHGs emissions seen to contribute to climate change. If implemented cost-effectively and safely, CCUS could enable countries to maintain their diversified portfolio of electricity-generation options, while critically reducing financial and security risks, improving technology reliability and environmental performance, and minimizing energy price volatility, as well as to reduce CO_2 emissions from large industrial sources (Tomski, Kuuskraa & Moore, 2012).

In 2010 for the United States, the Obama Administration commissioned a CCS task force, which concluded that the largest barrier to long-term demonstration and deployment of CCS technology is the absence of a federal policy to reduce GHG emissions. The task force further concluded that widespread deployment of CCS would occur only if the technology is commercially available at economically competitive prices. However, the lack of policy and economic viability has impaired projects for the demonstration and deployment of industrial commercial-scale CCS, which has resulted in project delays and cancellations (Folger, 2017).

Tomski et al. (2012) delineated several key points that highlight commercialization challenges to the wide-spread acceptance and use of CCS technologies.

- CCS is a business-driven path and a US policy to promote immediate and long-term CO_2 capture and storage via CO_2-EOR is necessary to facilitate commercial viability.

- The United States is the global leader in CO_2-EOR. Currently, CO_2-EOR contributes about 6 percent to US domestic oil production and has the potential to contribute thirty to forty percent and generate $6.8 trillion in revenue and economic activity.
- CO_2 supply is the limiting factor in CO_2-EOR expansion, and large volumes of CO_2 captured from power plants and industrial facilities (anthropogenic sources) are needed.
- CO_2 captured from anthropogenic sources costs roughly twice as much as natural CO_2 supplies. Policy action is needed to incentivize early movers and help close the "cost gap," or difference between the cost to capture and transport CO_2 and what EOR operators are willing to pay.
- A number of new policy proposals conclude that tax receipts and royalty revenues received by the government from oil produced from CO_2-EOR can more than pay for proposed CO_2 capture incentive programs.
- CO_2-EOR inherently provides CO_2 storage; however, in order to be considered CCUS, operators must demonstrate that the CO_2 is anthropogenic, and provide assurances through monitoring, verification, and accounting (MVA).
- Legal and regulatory uncertainty regarding MVA requirements for CCUS and long-term liability for carbon storage must be resolved.

Since the report of the IPCC (IPCC, 2007a; IPCC, 2007b; IPCC, 2007c; IPCC, 2014) and the formulation of the European Union's (EU) "20-20-20 strategy," (EEA, 2017 & OEU, 2011), there has been increasing attention for CCS as a means of reducing carbon dioxide emissions. Given that CCS is an industry that has large "sunk costs" and a long profitability horizon, these unreasonable ROI parameters for companies require national governments to play a significant financial role in advancing CCS to technology transfer and commercialization goals. Additionally, while CO_2 emission reduction has made progress, it becomes increasingly clear in recent years that it will be hard for national governments to reach required emission reduction targets without the deployment of CCS (EEA, 2017).

Addressing the minimalized list of complex challenges cited above by Tomski et al. (2012) certainly requires a strategic vision and working plan at the global, national, and local levels. Fundamental for any organization (e.g., for profit, nonprofit, and governmental) that finds itself placed in such a position is meaningful strategic planning (Brauer, Lee & Brauer, 2018). Strategic business planning enables innovative, science-based systems engineering solutions that are developed in a way that inspires public/customer confidence (i.e., from technological, safety, and financial perspectives). The emerging technology roadmap becomes one of strategy to effectively reduce technology development process uncertainty and to inspire "customer" confidence through successful technology demonstration (Beck, 2013).

David Beck (2013) in conjunction with Sandia National Laboratories proposed that technology development should be viewed from a formal strategic-based life cycle process perspective. This is particularly true where accountability and profitability are matters of concern; less so, where entitlement is embedded in an R&D culture, which is often evidenced in the widespread use of ad hoc processes (e.g., government subsidized projects). This direction adheres to the notion that technology maturation can be planned and follow a formal

technology development process, which implements the scientific method and follows a development framework for a multicycle technology maturation process that is suitable for use in high-risk ventures (e.g., CCS).

As suitable CCS pore space is scarce in most countries and the financial barriers high for collaborative partners, more and more governments have opted to develop a "National Master Plan" to develop a coordinated approach towards CCS. Numerous countries are engaged in master planning. For example, Australia, United Kingdom, and Netherlands have led the way in developing CCS master plans (GCCSI, 2017). It is expected that the number of countries formalizing national CCS policy will grow as the number of global commercial-scale industrial demonstration projects increase begin to materialize.

The purpose of a national CCS Master Plan is to outline a detailed strategy for the long term on which companies in the CCS value chain can build their business models. The Global CCS Institute (2017) advocates that the CCS Master Plan take a long-term view (at least 30-40 years), and that the CCS-policy of the government devising the plan is as transparent, robust, and predictable as possible for this period. Also, it is very important that the role of CCS in the national emission reduction strategy (consisting of promoting energy efficiency, increasing the use of renewable energy, and making the use of fossil fuels cleaner with CCS) is clearly outlined. Preferably, it should also fit in the national strategy for the use of infrastructure including the planning of use of underground reservoirs.

A National Master Plan can contain several elements, but the core purpose is to provide insight in connecting "sources" of CO_2 to "storage facilities" over a long period of time in the most cost-effective way. It can also provide recommendations on a variety of issues such as the organization and business model, the subsidy regime, the legal regime and technical requirements.

The Global CCS Institute (2017) references the following elements for inclusion in a CCS Master Plan:

Assessment of:

- Largest (grouped) sources of CO_2 emissions in a country (the so-called "point sources")
- Expected volumes of CO_2 that can be captured in time (over a longtime horizon, such as 30-40 years)

Volumes estimated using several scenarios

- Available storage reservoirs of sufficient size, including their availability over time
- Cost-effective pipeline routes to connect the point sources to the sinks, taking into account the captured volumes of CO_2 in time

In addition, a Master Plan could also contain an assessment, depending on how well-prepared a country already is for CCS, of:

- CO_2 specifications for capture, transport and storage per CCS project (these can also be established nationally)
- Costs of re-using existing infrastructure from industries such as the oil and gas industry

- Competition for use of the underground in spatial planning
- Degree of governmental participation in CCS
- CCS business model, including subsidies, the commodity value of CCS and the optimal taxation regime
- Legal regime for CCS
- Pathways for import and export of CO_2 to a country, based on their storage capacity

A fundamentally desired outcome of any strategic plan is to reduce “uncertainty” in both technology development, financial and economic viability, and public acceptance. In 1992, the Industrial Research Institute (Beck, 2013) sponsored an investigation that systematically identify causes of uncertainty in the R&D process. The underlying assumption was that “application of appropriate solutions,” which reduce these uncertainties, would “shorten project cycle times and improve the efficiency and productivity of the entire innovation process” (Burkart, 1994).

Using common Total Quality Management tools, forty-five major causes of uncertainty in research were identified that were grouped into eight categories. The most frequently encountered causes of uncertainty were "customer requirements not defined" and "delays in decision." The eight categories are (Beck, 2013): 1) Market, 2) Competitor, 3) Technical, 4) Business Processes, 5) Management Style, 6) People/Culture, 7) Communication, and 8) External Efforts.

Of particular interest is the technical category. Here, Beck (2013) located thirteen of the causes of uncertainty: 1) not invented yet, 2) science insufficient, 3) effort insufficient, 4) core competency mismatch, 5) skill mismatch, 6) customer interface insufficient, 7) product feature mismatch, 8) technical planning insufficient, 9) technical support insufficient, 10) manufacturing capability insufficient, 11) financially unfeasible, 12) economically unfeasible, and 13) timing inappropriate.

As stated previously, for large financial investment projects, the issue of “planning” is a key component for managing “uncertainty.” The planning of concern is that for the engineering research and development processes, and controls related to technical tasks (i.e., technical goals, objectives, effects, and actions) required to leverage an organization’s capabilities (i.e., core competencies, processes, and strategic assets) to transition an idea into a product that has good commercialization potential (i.e., acceptable risk). Figure 8 depicts the SBC Energy Institute’s (Soupa et al., 2012) delineation of several “business models” that could be foundational, as applicable, for the strategic planning approach for increasing the CCS probability of commercialization success.

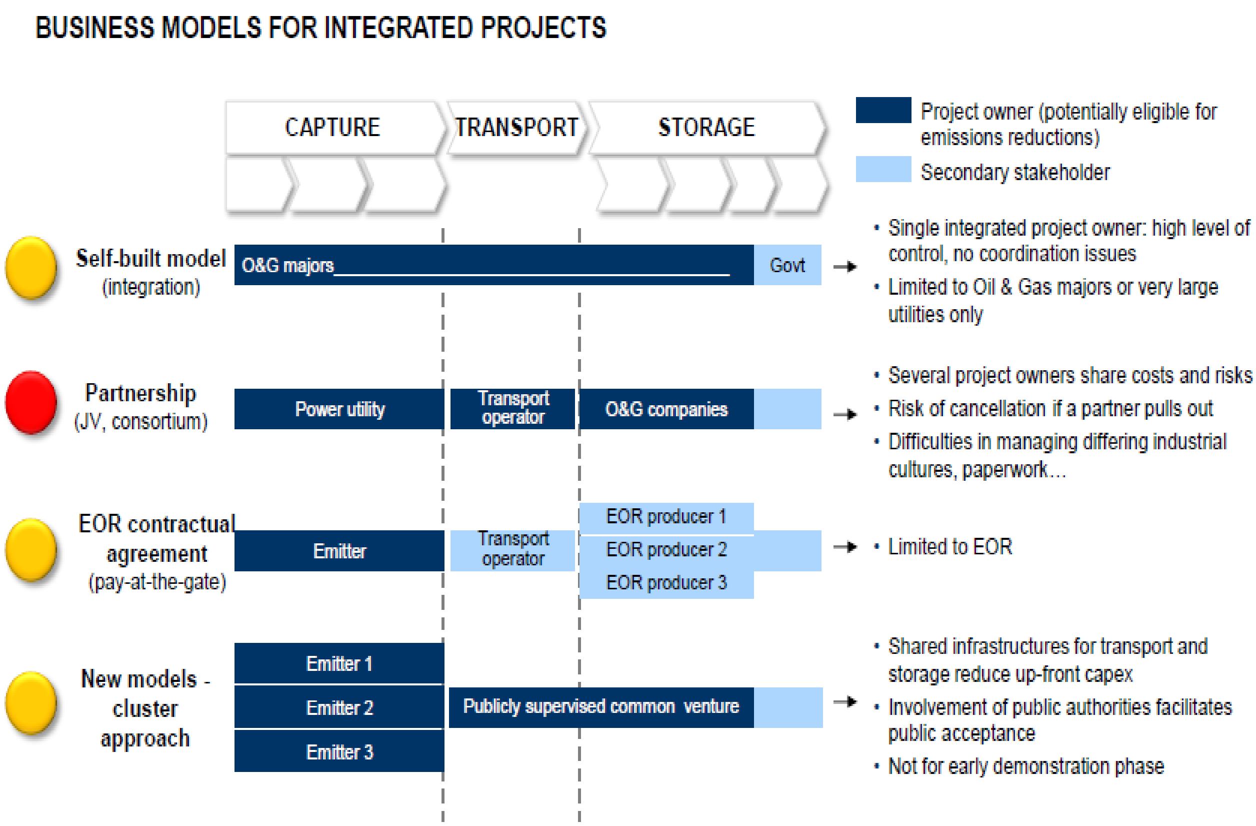


Figure 8 Business Models for Integrated CCUS Projects (Soupa, Lajoie, Long & Alvarex, 2012)

TECHNOLOGICAL

Different approaches are considered and adopted by various countries to reduce their CO_2 emissions, including (Leung et al., 2014):

- Improve energy efficiency and energy conservation
- Increase usage of low-carbon fuels (e.g., natural gas, hydrogen, and nuclear power)
- Deploy renewable energy (e.g., solar, wind, hydropower, and bioenergy)
- Apply geoengineering approaches (e.g., afforestation and reforestation)
- Implement CO_2 capture and storage (i.e., CCS)

As presented previously in Table 1 (Leung et al., 2014), there are a variety of technological approaches to address source emissions reduction. It is unlikely that adopting a single technological approach or strategy can adequately meet the IPCC goal of CO_2 reduction. With the world's vast coal reserves in conjunction with increasing global energy needs, the use of "clean coal" remains at the crossroads with its contribution to anthropogenic greenhouse gas emissions.

The technological viability of CCS as a tool for clean energy is being demonstrated with the Petra Nova power generating facility, which is the first U.S. coal-fired power plant outfitted with CCS technology. This commercial-scale demonstration project has advanced CCS

deployment across the electricity industrial sector and has represented CCS as a viable technology for reducing GHG emissions (Klump & Gronewald, 2017).

Countering the success of this project was the cancellation of the USDOE sponsored project for the Kemper power generation facility. Unlike Petra Nova and the Boundary Dam CCS plant in Canada, both retrofits of older facilities, the Kemper project was a new power generation facility initiated with the intention to integrate CCS technology into the plant design from the outset. All three plants received subsidies from the federal government, but other factors were at play in determining the success or failure of each venture.

In some aspects, the Kemper plant resembled the original design for the FutureGen plant planned for during the George W. Bush Administration. FutureGen conceptually was a power plant to be built from scratch in Central Illinois, USA, to be largely emissions free using CCS (Folger, 2017). Cost issues, schedule delays, and community resistance hampered FutureGen, even though it was slated to receive nearly $1 billion in Federal funds, far more than the amount provided to Kemper.

This FutureGen project was resurrected during the Obama Administration as FutureGen 2.0, but, again, suffered the inability to overcome escalating costs and the lack of industry financial commitment to advance to commercial-scale demonstration. It is important to note that escalating costs and schedule delays are anticipated for nearly all first-of-a-kind large, capital-intensive projects. Demonstration phase projects commonly fall along the most expensive part of a cost curve from inception to commercial deployment.

Nevertheless, the mixed success in 2017 of the Petra Nova and Kemper plants put the development of CCS somewhat at a crossroads, particularly with the apparent lack of interest in further support for such projects signaled by the current Trump Administration. The United States FY2018 budget request significantly reduced USDOE funding for CCS. Additionally, the Trump Administration expressed interest in supporting early-stage research versus large demonstration commercial-scale projects, such as Petra Nova or Kemper.

Even with the current uncertainty over the future of CCS, some in Congress have signaled continued support for DOE's R&D efforts with respect to CCS. For example, the House Energy and Water Development appropriations drafted legislation to support CCS R&D at a level comparable to FY2017. The Senate version of the appropriations legislation also looked to fund CCS R&D at a lower level than the House version, but still at a higher level than the Administration's budget request. In addition, some Senators and Members of Congress have continued to introduce legislation in the 115th Congress intended to advance and shape CCS.

Within the portfolio of low carbon technologies, CCS technologies have remained somewhat competitive in the acquisition of patents. The SBC Energy Institute (Soupa & Lajoie, 2012) illustrates in Figure 9 that CCS technologies lag behind wind and solar photovoltaic new technology development. However, these are lower cost technologies that have fared-well with the gaining of governmental subsidies to enable them to be commercially successful.

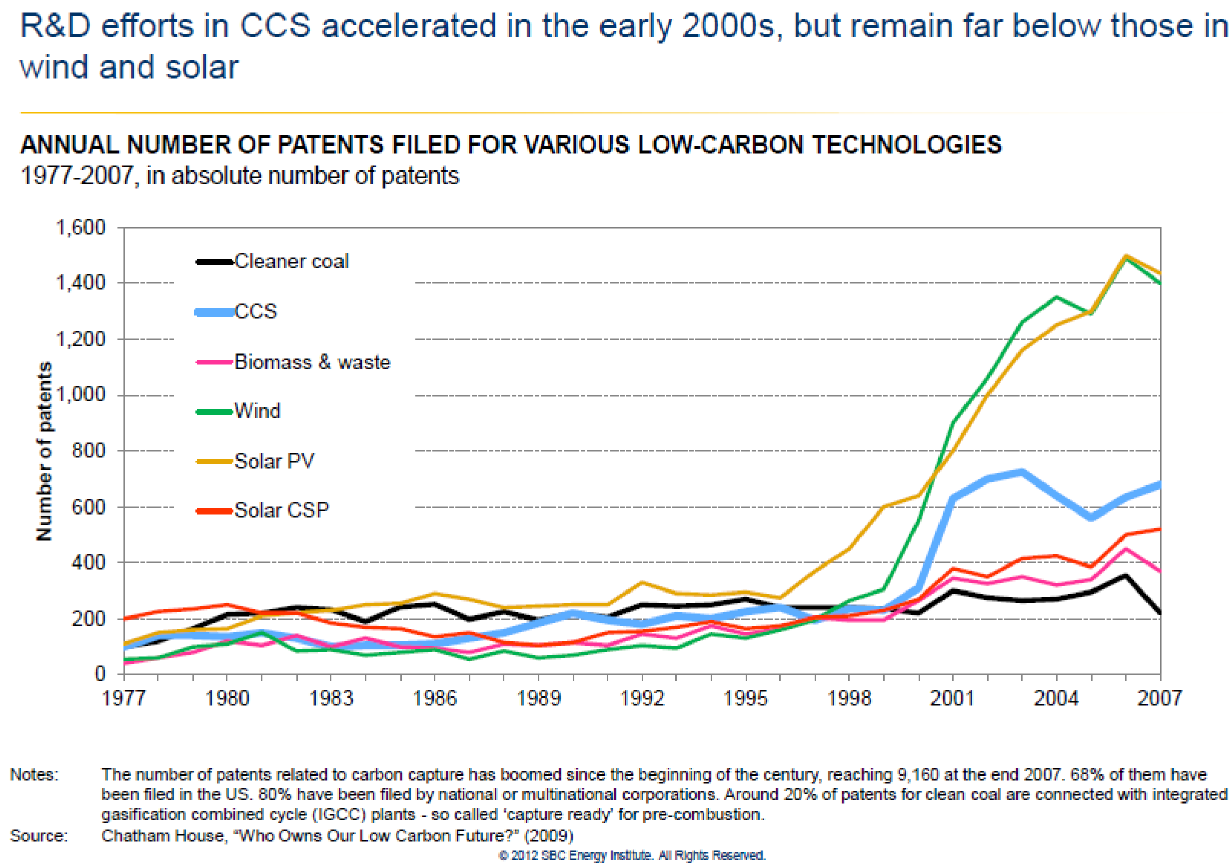


Figure 9 Patents for Low Carbon Technologies (Soupa &, Lajoie, 2012)

The Global CCS Institute (2017) relates that accumulated experience of CO_2 injection worldwide over several decades has proven there are no technical barriers preventing the implementation of storage. Over forty sites have, or are, presently safely and securely injecting anthropogenic generated CO_2 underground, predominantly for EOR and dedicated geological storage. Additional geological storage experience has come from industrial activities addressing waste water, acid-gas, and natural-gas storage.

It is accepted that CO_2 storage experience indicates that geologic storage is safe, secure, and highly effective (Brauer, 2015). Storage sites can be selected, characterized, operated, and sealed, based on well-established practices and techniques gained from decades of relevant industry experience in a variety of settings around the world. Over these years, many millions of tonnes of CO_2 have been injected and stored, with no tangible evidence of leakage (GCCSI, 2017).

FINANCIAL

Abatement costs for coal-fired electricity with CCS range from \$54/tCO_2 to \$92/tCO_2 (per tonne of CO_2) (Soupa & Lajoie, 2012). Adjusting for 2018 future value (assuming a modest 3% rate) this range is approximated to be \$65/tCO_2 to \$110/tCO_2. Figure 10 (Soupa et al., 2012) provides an indication of the relative increased costs to energy production facilities applying CCS

technology, which ultimately get absorbed by the consumer. However, CCS remains a competitive technology to abate CO_2 emissions in power generation, as using CCS is significantly less expensive than replacing coal power plants with solar plants (2018 value estimated at $126-$286/tCO$_2$) or offshore wind farms (2018 value estimated $108-$211/tCO$_2$) (Soupa & Lajoie, 2012). There are few economical alternatives to CCS for cutting emissions from industrial applications such as steel and cement production, chemicals plants, and gas-processing units.

CCS is seen as a costly technology because of its high up-front costs and uncertain long-term benefits. Each commercial-scale CCS project can cost up to 1 billion dollars in capture costs alone, although they are capable of abating over 1 MtCO$_2$ per year for several decades (the equivalent of taking over 200,000 cars off the roads per year). Private/public companies typically have a difficulty in rationalizing the ROI for developing and implementing CCS technology. On the flip side, the financial support required for each project is so large that governments rarely have the political will power, or available resources, to subsidize CCS to the extent required to engage industrial partners.

However, the Organisation for Economic Co-operation and Development (OECD) (an intergovernmental economic organization with 35-member countries, founded in 1961 to stimulate economic progress and world trade) has committed over $22 billion USD to help sponsor global CCS demonstration projects. The grants allocated have represented an average of $15/tCO$_2$ avoided over the lifetime of each project. However, the OECD has been unable to establish abatement financial incentives for companies to recover CCS investment costs. Globally, the market price of CO_2 averaged $15/tCO$_2$ in 2011, and most carbon taxes were set below $25/tCO$_2$ (Soupa & Lajoie, 2012).

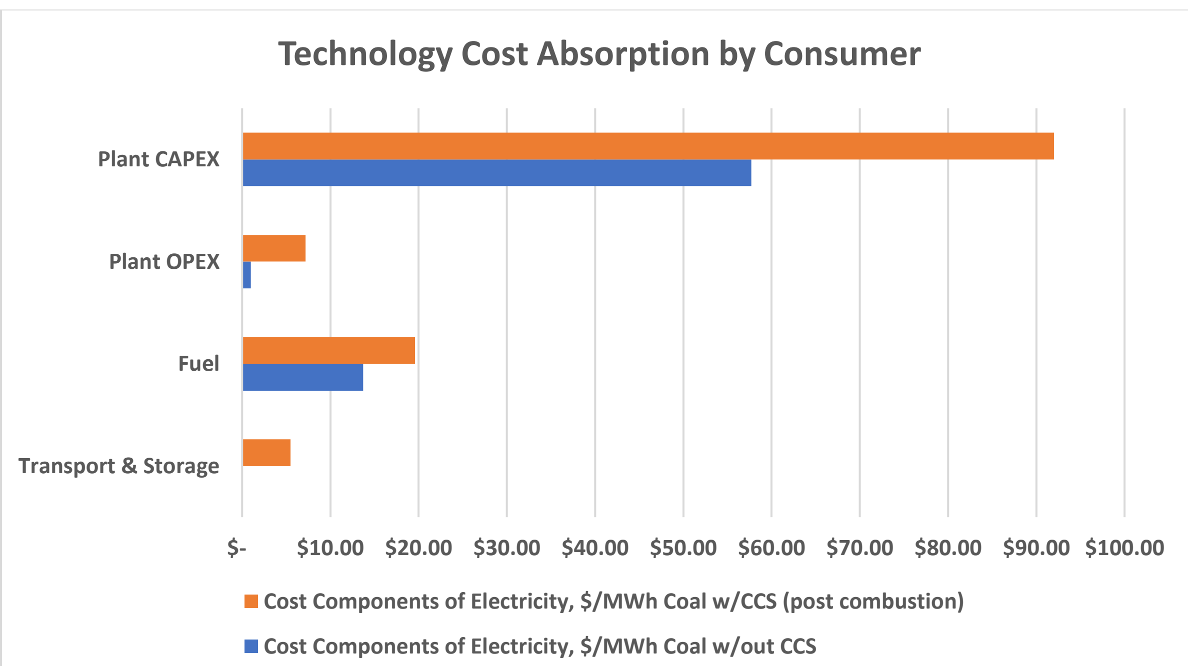


Figure 10 Technology Cost Absorption to Consumer (Soupa, Lajoie, Long & Alvarex, 2012)

As indicated previously, the most financially viable, and proven technology, is the use of CO_2 for EOR. The EOR process fundamentally uses captured, purified, and dehydrated CO_2 for injection to existing oil wells to act as a lubricant to release “sticky” oil from the well’s geological structure. Once the well has released all its oil, the CO_2 remains captured in the well structure, a natural storage facility.

Approximately 1 $MtCO_2$ is stored for every 2.5 barrels of oil produced. As CO_2-EOR expands in the United States, greater volumes of anthropogenic CO_2 will be needed, resulting in permanent sequestration of CO_2 that would have otherwise been emitted to the atmosphere. One philosophical disadvantage of this process is that once the oil produced from CO_2-EOR is consumed, it then likely contributes to anthropogenic CO_2 emissions.

A number of studies (Tomski et al., 2012) have investigated the overall life cycle emissions associated with CO_2-EOR and CCS under different scenarios. Conclusions have varied depending on where the boundary of the analysis is drawn, how these values compare with other petroleum or alternative fuel sources, and whether those sources were produced domestically or imported. As noted previously, some studies conclude that CO_2-EOR results in net carbon emissions when accounting for the carbon in the oil produced (Jaramillo, 2009). Other studies conclude that the barrel of domestic oil produced from CO_2-EOR will displace either a barrel of oil produced through traditional methods, or an imported barrel, both with larger carbon footprints. However, some studies also consider the benefits in terms of emissions savings and cost, and of leveraging the CO_2-EOR pipeline infrastructure that is incremental to existing oil-field developments for large-scale geologic carbon storage (Tomski et al., 2012).

While discussions continue on where the boundary for GHG accounting should be drawn, the bottom line is that CO_2-EOR utilizes CO_2 that would have otherwise been emitted into the atmosphere, which advances the only immediate long term demonstrated commercial pathway for CCUS. The extent to which CO_2-EOR will be leveraged for wide-scale CCUS deployment depends largely on how the CO_2-EOR market continues to develop, and on what type of policy actions will be taken to incentivize pure CO_2 CCUS (Tomski et al., 2012).

Table 2 (IEA, 2008; IEA, 2009) provides an estimated cost of avoided CO_2 via CCS falls anywhere in the range of \$30–\$118USD/tCO_2 for coal-fired power plant projects. Note that the broad variance in estimates is due to a lack of empirical data and a myriad of factors such as capture technology choice, ownership of components, and distance of transport. For example, a new IGCC plant with CCS in China would experience an increase of \$65–\$106 million USD in capital costs, which would translate to an electricity tariff of US\$94–113/megawatt-hour (MWh) and overall costs between \$33–\$40USD/tCO_2 avoided, including capital and operational expenditures (Gao, 2010). The IEA has estimated the total cost for a new average-sized coal-fired power plant that captures up to 90 percent of its CO_2 emissions to be greater than \$1 billion USD over the next ten years (IEA, 2008; IEA, 2009).

At present, the cost burden of CCS on operators makes projects prohibitively expensive under any scenario without public support (Folger, 2017). Because CCS technology is broadly still at the pre-commercial stage and is unable to generate profits on its own in the absence of regulations that penalize CO_2 emissions, there is little incentive for developing countries and their enterprises to act on CCS research and development. As a general rule, developing

countries lack the necessary resources to unilaterally effect investments of such magnitude in novel technologies at the scales needed.

Table 2 List of cost estimates for early CCS projects (IEA, 2008; IEA, 2009)

Source	Estimates
IPCC (2005)	New pulverized coal: Cost Avoided US$30–70/t$CO_2$; increase in electricity cost: 43–91 percent New IGCC: Cost Avoided US$14–53/t$CO_2$; increase in electricity cost: 21–78 percent
IEA (2008)	US$40-90/t$CO_2$ abated
IEA (2010)[b]	Pilot to large scale: Avg. US$1 billion investment per project over the next 10 yrs
IEA (2011)	Post-combustion capture (OECD only) average US$58 with range US$40-69/tCO_2 avoided Pre-combustion IGCC US$43 with range US$29-62/tCO_2 avoided Oxy-combustion average US$52 and range US$27-72/tCO_2 avoided
GCCSI (2009)	Pulverized Coal (Super and ultra supercritical): US$87-91/t$CO_2$ avoided IGCC: US$81/t$CO_2$ avoided
Bhargava (2010)	Standard coal, no CCS: ~$0.7 M/MWh total costs; US$0.05/kWh Supercritical + CCS: ~US$1.4 M/MWh total costs; US$0.09/kWh IGCC + CCS: ~US$1.6M/MWh total costs; US$0.11/kWh
Al-Juaied and Whitmore (2009)	First of a kind plant: US$100–150/t$CO_2$ (capture only)
Gao (2010)	IGCC China: incremental capital cost of US$65–106 M (60–100 percent capture) Expected electricity tariff without incentive: US$94–113/MWh (60–100 percent capture)
Coal Utilization Research Council[c]	$17.3 B/yr incremental cost for early adopter 45 GW (30-yr plant life) over 20 yrs $4.5 B/yr incremental cost for pioneer plant 10 GW (30-yr plant life) over 15 yrs
Lignite Energy Council[d]	$1 B/yr incremental capital cost for 10 yrs for five retrofit and five new demos with storage $3.8 B/yr incremental capital cost for 10 yrs for seven integrated projects (>600 MW)
McKinsey (2008)[e]	New Project: 0.6–1 billion additional cost per plant; US$78–118/t$CO_2$ abated
UK-China NZEC (2009)[f]	IGCC: 0.5 billion; Pulverized coal: 0.7 billion; Retrofit: 0.9 billion New IGCC China: ~US$42/t$CO_2$ avoided
COACH (2009)	New IGCC China: US$33–40/t$CO_2$ avoided

SOCIETAL

Community Acceptance

Stakeholder support (i.e., community acceptance) is a key building block for a successful market implementation and societal acceptance of emerging technologies. However, misconceptions and biases in people's perception (e.g., energy sources) could influence their support of proposed energy developments integral to the success of a nation's adoption of the use of specific technologies. Lee and Gloaguen (2015) identified that in gaining community acceptance education is one of the key factors shaping how people view technology-related issues (Figure 10). In equipping young adults with the cognitive skills and knowledge necessary to navigate in the confusing energy environment, science outreach and education play a key role in diffusing such misconceptions and biases and to pave the way for informed decision-making (Lee, 2016).

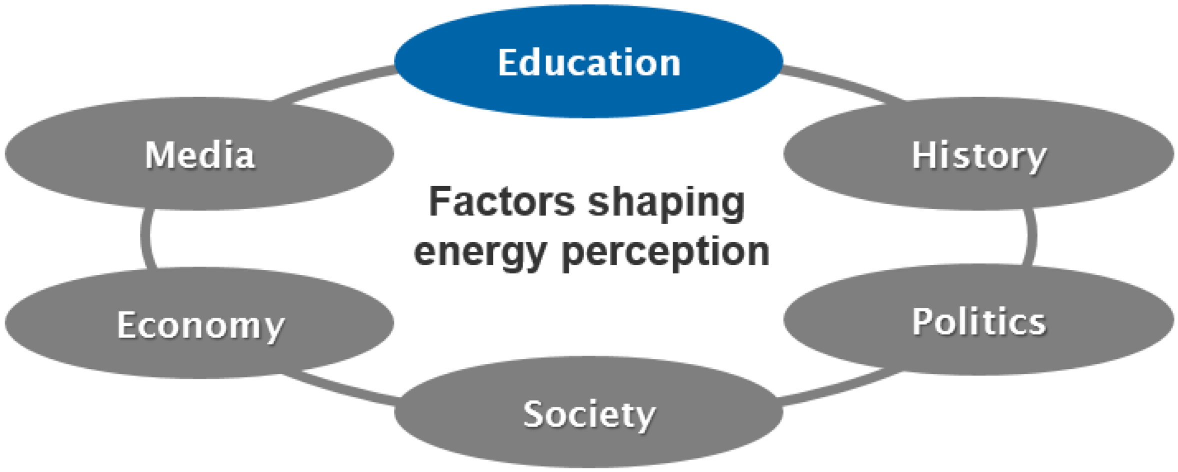


Figure 10 Factors Shaping Perception (Lee & Gloaguen 2015)

An example of addressing CO_2 issues is the proposal of a concept to support the national transformation from a "linear to circular carbon economy" and to close the carbon cycle (Lee, Keller & Meyer, 2018). A key component of this concept is waste processing for chemical recycling.

Besides dumping, waste management globally still currently uses waste incineration. The latter represents a linear cradle-to-grave model whereby carbon in the waste is fully released as CO_2 emissions. In Germany, under the current EU Emissions Trading System (ETS), CO_2 emissions from waste incineration plants receive ETS allowances (i.e. face no penalty payment) (Lee, Keller & Meyer, 2018). Nevertheless, this does not change the fact that the combustion of 100 units C (e.g. carbon atoms) of waste for electricity and heat will result in 100 units C being released as CO_2. The 20 million tons of waste, which is currently combusted in Germany, thus present an opportunity for binding carbon into chemical products via chemical utilization. This circular concept illustrates CCUS and supports resource efficiency whereby valuable carbon resources are channeled back into the value chain for multiple utilization cycles (Lee et al., 2018).

This concept highlights one example how energy policy and technological decisions are embedded in complex social and political contexts where the success of policies and investment decisions is often dependent on public acceptance. How energy sources are perceived plays a key role in influencing public acceptance (Slovic, 1987; Truelove, 2012). As such, insights into the stability of people's energy source perceptions in the aftermath of catastrophic energy events are of significant strategic and practical implications for energy policy and managerial decision-makers.

Energy debates in the public sphere are often loaded with emotions (Grässler, Levitz & Knight, 2011; Roeser, 2010; Schulz, 2012; Smith & Prosser, 2011). This is especially true following energy catastrophes, such as the Fukushima nuclear incident. This calls for a more

thorough understanding of affective rationality (Slovic et al., 2007, 1350) in the energy context. Researchers from various fields ranging from neurology to decision sciences are increasingly highlighting the explanatory power of affective rationality, which emphasizes the interplay of affect and feelings with cognition and reason-based decision-making in influencing and guiding perception, judgment, and decision-behaviors (Damasio, 1994; Kahneman 2003; Loewenstein et al., 2001; Peters et al., 2006; Rottenstreich & Hsee, 2001; Slovic et al., 2007).

In particular, the role of affect-laden imagery in influencing judgment and decision-making has been emphasized (Keller, Visschers, & Siegrist, 2012; Leiserowitz, 2006; Slovic, MacGregor & Peters, 1998; Truelove, 2012), whereby the affective quality of a person's mental imageries has been found to be strongly related to attitudes, preferences, and behaviors across a multitude of decision environments (Slovic et al., 1998). Researchers have highlighted the need of a qualitative content-analysis of energy imageries in addition to a quantitative examination of affect associated with such energy imageries in order to gain insights into the underpinnings of energy judgment and support (Keller, Visschers, & Siegrist, 2012; Slovic, Layman & Flynn, 1990; Truelove, 2012).

Kahneman (2011) termed the unconscious and automatic process of associating a word with imageries and feelings "associative activation." He highlighted how such associative impressions generated are the source of the impulses underpinning people's decisions and behaviors. In the complex environment where energy judgment and decision-making take place, affective imageries could thus work as a heuristic to facilitate quick and efficient decision-making relating to various energy sources. This subsequently influences peoples' motivation to seek out information to support their existing views in addition to potentially biasing their analysis of conflicting energy-related information and their responses toward an energy issue. Present findings thus represent a first step toward gaining a deeper understanding of diverse affective imageries representing people's motivations/concerns underpinning their support and concern regarding various technologies) (Lee et al., 2018).

Societal perceptions and positioning are generally based on past technology development and implementation decisions, which influence and constrain future choices leading to a "lock-in" to a certain energy development path and reliance on specific energy sources (Lee, 2016). This represents a significant obstacle to the success of planned technology transitions. Additionally, lock-in effects can extend beyond the technological and institutional environments to the human dimension of energy systems.

A lock-in in how a technology is viewed by individuals in a society could mean that prevailing energy perception, in providing a basis for judgment and decision-making, may discourage further analysis and lead to habitual responses and reactions that could subsequently hinder the adoption and societal uptake of new or innovative energy technologies. Beyond the individual context to the wider societal context, this has significant implications for managing technological transitions as it poses an additional dilemma for climate change and CCUS energy policy makers who already have to deal with inertia from barriers created by techno-institutional path dependence.

In order to achieve sustainable success in overcoming lock-in in socio-technical systems and facilitate the success of technological, policymakers cannot only focus on addressing the technological and institutional dimensions associated with changing the CCUS "hardware" (Lee et al., 2016). This includes, for example, replacing fossil/nuclear power plants with renewables

and restructuring the energy markets and institutional environments to encourage renewable energy generation.

On path-dependence and lock-in effects, the concept of path dependence can be traced back to eco-nomic research in the 1980s. Its origins can be found in evolutionary economics, where the core idea highlights that technology developments can be traced along pathways paralleling their industrial histories (Nelson & Winter, 1982). Researchers especially emphasized how "history matters", as decisions to embark along a developmental path tend to rely on and are constrained by earlier choices (Patalano, 2007). In particular the increasing returns phenomenon is noted to play a crucial role in path-dependence processes. Increasing returns refer to the growing benefits arising from the continued adoption of a process (Mahoney, 2000); Patalano 2007; Pierson 2000). Hence, a first step along a certain path makes additional steps in this direction less costly and more likely, thus reducing the probability of divergence from a chosen path. According to Arthur (1989), such increasing returns can result in a society gradually locking itself into outcomes that are not necessarily superior to available alternatives.

Education & Outreach

The increasing international awareness of global warming concerns has highlighted unique issues of societal acceptance of CCUS technologies that promote environmental sustainability. Much of CCUS push-back regarding societal acceptance has been the perception that negative side-effects of CCUS technologies are purposely hidden from public view, which leads to a lack of societal trust, validated or not.

Education has been identified as one of the key factors shaping how people view technologies (Lee & Gloaguen, 2015) and people from different education backgrounds are observed to diverge in their perception of technologies (Barke, Jenkins-Smith & Slovic, 1997; Jenkins-Smith & Herron, 2007; Sjöberg, 2004). Lee (2016) states that in designing educational (i.e., science) curriculum to address misconceptions and biases in perception for a specific technology, it is necessary to keep in mind that the public is not homogenous in its risk perception (Pidgeon, 1998).

Of particular relevance for educators are findings that young adults pursuing different education pathways (e.g. academic vs. non-academic; engineering/natural science disciplines vs. business/social science disciplines) already exhibit significant education-specific divergence in their perception of technologies (Drottz-Sjöberg & Sjöberg, 1991; Nippa & Lee, 2015). In designing CCUS academic and nonacademic curricula to address misconceptions and biases in CCUS technology perception, it is necessary to keep in mind that the public is not homogenous in its risk perception (Pidgeon, 1998). However, structured and targeted education has been identified as one of the key factors shaping how people view technology (e.g., energy sources) (Lee & Gloaguen, 2015; Barke, Jenkins-Smith & Slovic, 1997; Jenkins-Smith & Herron, 2007; Sjöberg, 2004; Drottz-Sjöberg & Sjöberg, 1991; Nippa & Lee, 2015).

A logical outcome of the desire to establish a firm understanding of technologies and correcting misperceptions through education has been the creation of partnerships between higher education, business/industry, and communities to positively sculpt public perception of a project's environmental impact and gain the public trust in its conduct. The need for collaborative partnerships is heightened with the potential confusion between multiple

technologies perceived in societal circles as having potentially negative sustainability impacts (e.g., hydraulic fracturing and carbon capture and storage).

IL-ICCS Project

An example of an effective CCS education and outreach project was that conducted as part of the US Department of Energy, National Energy Technology Laboratory, project “Illinois-Industry Carbon Capture and Storage” (IL-ICCS). The project partners assembled included Archer Daniels Midland Company (ADM), Schlumberger Carbon Services, Illinois State Geological Survey Division of the University of Illinois at Urbana-Champaign, and Richland Community College.

Beginning in 2010, this Project’s task was to demonstrate the viability and effectiveness of commercial-scale CCS by putting the infrastructure in place and initiating the capture and storage of over 2.5 million tonnes of CO_2 over three years from ADM’s ethanol production facility in Decatur, Illinois. The IL-ICCS project is to demonstrate commercial-scale CCS by capturing CO_2 emissions from the ADM, Decatur, Illinois, USA, ethanol facility and storing them deep underground. In concert with this, the ongoing community education and outreach activities conducted by the College successfully engaged the public to a wide-spread understanding that CCS technologies safely reflect the best interests of the community.

To facilitate CCS education and outreach, the National Sequestration Education Center (NSEC) was established and constructed on the College campus in the Richland Agribusiness Applied Technology Park. The NSEC quickly served as a local, regional, national, and international focal point for CCS community outreach and education by providing an innovative experiential learning and knowledge transfer environment. The NSEC provides unique educational value to researchers and visitors from around the world by experiencing the sequestration technologies demonstrated in close proximity to the NSEC.

The uniqueness of this project has resulted in: 1) the establishment of a global educational center (i.e., the NSEC) with close proximity to two USDOE CCS projects; 2) the creation of the world’s first CCS community college Associate of Science and Associate of Applied Science degree specialties; and 3) the delivery of CCS educational outreach activities to over 3,600,000 people since 2011. Additionally, the economic development generated with this project resulted in over 900 domestic jobs, including 250 local jobs and the creation of over 10 permanent jobs. The additional local economic impact was estimated to be over $30,000,000 USD. However, more importantly this project transitioned research to commercial-scale demonstration advancing national and global practices and policy. The IL-ICCS project demonstrates CCS as a socially value-added emerging technology, economic-stimulator, educational platform, and environmental sustainability facilitator.

IL-ICCS Background

The USDOE Office of Fossil Energy’s National Energy Technology Laboratory (NETL) manages the IL-ICCS project, which is the largest project in the USA to store CO_2 in a deep saline formation. The overall objective of the project is to demonstrate an integrated system for collecting CO_2 from ADM’s ethanol production plant in Decatur, Illinois and geologically sequestering it in the Mt. Simon Sandstone formation.

At the ADM facility, CO_2 is produced as a byproduct from processing corn into fuel-grade ethanol. The IL-ICCS project scope (Gollakota & McDonald, 2012) includes (1) design,

construction, demonstration, and integrated operation of CO_2 compression, dehydration, and injection facilities, (2) MVA of the stored CO_2, and (3) development of a communication, outreach, training, and education initiative.

The IL-ICCS project began in 2010 and was originally scheduled to begin CO_2 injection by 2015 to a depth of approximately 7,000 ft. Actual injection began in 2017 upon meeting U.S. Environmental Protection Agency and U.S. Geological Survey concerns regarding certification of a Class VI well (NETL, 2017). Over a three-year period, approximately 2.5 $MtCO_2$ are expected to be injected into the Mt. Simon Sandstone, which has an estimated CO_2 storage capacity of up to 151 billion tonnes (USDOE, 2012a). The project presents a 'unique opportunity' (NETL 2012) to gather crucial scientific and engineering data for large-scale CO_2 storage in saline formations to mitigate global climate change. Additionally, successful implementation of the project could facilitate long-term CO_2 utilization options, such as EOR in the Illinois Basin. The IL-ICCS project received $141.4 million in 2009 AARA funding and another $66.5 million in project partner cost-sharing.

IL-ICCS Education and Public Outreach

Integral to the IL-ICCS project were CCUS education and public outreach activities. This addressed K-12 and higher education curriculum development, construction and programming of the NSEC, and broad community CCS outreach.

A significant motivator in engaging a community college (i.e., Richland Community College) in this project was its educational mission. A backdrop for leveraging the College's expertise in conducting outreach for this emerging technology were a set of best practices developed by the National Energy Technology Laboratory (USDOE, 2013). These include:

- Best Practice 1: Integrate Public Outreach with Project Management
- Best Practice 2: Establish a Strong Outreach team
- Best Practice 3: Identify Key Stakeholders
- Best Practice 4: Conduct and apply Social Characterization
- Best Practice 5: Develop an Outreach Strategy and Communication Plan
- Best Practice 6: Develop Key Messages
- Best Practice 7: Develop Outreach Materials tailored to the audiences
- Best Practice 8: Actively Oversee and Manage the Outreach Program throughout the Life of the CO_2 Storage Project
- Best Practice 9: Monitor the Performance of the Outreach Program and Changes in Public Perceptions and Concerns
- Best Practice 10: Be Flexible – refine the Outreach Program as Warranted

While the CCUS technology itself did not present a safety problem, of concern was the local and regional communities' perception of the intended use of the technology. That is, what did it mean that a local global corporate giant was embarking on using an emerging technology that was at best was a "foreign topic" that did not necessarily present a positive image. That is where the community college provided the greatest advantage as a project team member and highlighted the need to pay close attention to Best Practice 4.

Key items in conducting and applying social characterization (Best Practice 4) include understanding and establishing relationships leveraging: local economic conditions, local empowerment, underlying views, environment, energy, trust**,** media, local education, local traffic conditions, and local hazards (USDOE, 2013). Of these, perhaps the most significant for any project success is having a trusting relationship with the communities in which the project activity is taking place. The existing trusting relationship between the community college and the regional communities it serves played a significance role in the project's acceptance and the embracement of the emerging CCS technology.

To ensure success in education and outreach, a psychodynamic strategic perspective was taken to guide the College in its approach to communication, education, and outreach for the project (Brauer, 2014). This involved understanding the local and regional stakeholder personality predispositions to strategically advance the project's education and outreach activities. The scientific and technical nature of this project necessarily provided a need to understand and leverage local and regional demographics, culture, and the existing college/community trust relationship in establishing an aggressive outreach and education activity. A team, or group, effectiveness theoretical construct was applied to facilitate the development and implementation of "communication" and "outreach" tactical strategies to increase the likelihood of CCUS acceptance by local and regional communities.

Typically, team effectiveness models have displayed two common traits (Shaw, 1976). First, they highlight the issues of process and outcome (i.e., how a group becomes productive and what a group produces). Second, they highlight organizational or environmental parameters, and the collective group. It was reasonably accepted that the behavior of individual community stakeholders could enhance or impede overall project effectiveness. Interpersonal conflicts, poor communication, lack of project team cohesiveness, and disagreement over goals, etc. have been recognized as some of the behavioral consequences of dysfunctional team member behavior (Reilly, Lynn, & Aronson, 2002). From this, it became self-evident that the behavioral predispositions of project team members and community stakeholders warranted close attention and management as they would play a major role in the societal acceptance, and success, of the overall CCS project.

Reilly et al., like other researchers, supported the premise that demographic variables (e.g. age, race, gender, and seniority), abilities and personality variables were examples of team member interpersonal characteristics that should be related to effective or ineffective community behavior. This also was especially true of personality variables, which are a "mixture of values, temperament, coping strategies, traits, character, and motivation" (Reilly et al., 2002).

Recognizing that societal "trust" was critical, getting to having a clear, coherent, and effective message, two seminal constructs were considerations (Brauer, 2013):

1. Psychodynamic considerations for "working team"
    a. Basic Assumption Theory…Wilfred Bion (Thelen, 2000)
    b. Focuses attention on team effectiveness as a collective function of individual team members
2. Learning and Affect of the "message"
    a. Two Factor Theory……David Stagg (Stang, 1975)
    b. Recognizes that a learning and satiation factor have additive, antagonistic roles in determining the effects of repeated exposure on affect.

These constructs provided guidance in maximizing the effect of project team personality, and persistence in "presenting the CCS message." The result was social acceptance of the implemented CCS emerging technology by the local and regional communities. This was due in large part to proactively discussing the project with "transparency" regarding the CCS technology, which enhanced the trusting relationship with the communities served.

CCS Educational Activities

The IL-ICCS project facilitated the United States' first higher education Associate degree programs with emphasis in CCS. These programs were based out of the NSEC, located on the college campus. The new programs included an Associate of Applied Science (AAS) degree in Engineering Technology with a CCS specialty and an Associate of Science (AS) transfer degree with a CCS concentration, a university transfer degree. Additionally, the CCS academic courses were articulated to university degree programs throughout Illinois.

The IL-ICCS project's CCS outreach includes K-12, teachers' workshops, and community and professional organizations (e.g., WAND Television "Make the World A Little More Sustainable," Illinois State Fair, Camp Connections, SMASH Camp, The K-12 Green Guide Series, and NSEC tours). The outreach activities provide the public with: 1) a general overview of CCUS technologies, including the benefits of CCUS, 2) an opportunity to ask questions and discuss concerns regarding CCUS, and 3) IL-ICCS project progress and results.

Additionally, outreach activities focus on renewable energy resources and sustainability features as part of a portfolio of low carbon technologies to reduce atmospheric CO_2 emissions. Outreach totals for 2011-2017 were over 3.6MM people for direct community outreach, classes, radio series segments, and television series segments.

RISK & LIABILITY

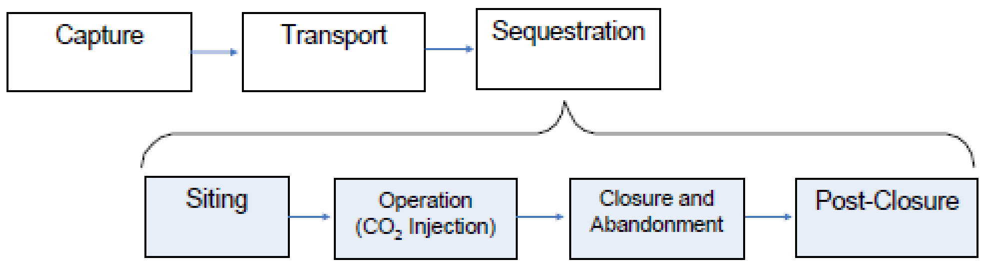
As with any industry and emerging technologies, commercial success and societal acceptance often depends on understanding the unique potential legal Issues. Logan (2007) provided early insight into CCS potential legal issues. This is of particular interest for CCS as over 95% of the potential CO_2 storage capacity in the United States (and the vast majority in the world) is in deep saline formations (USDOE NETL, 2012; Dooley, 2013; USGS, 2013). In these geologic formations, residual trapping could be the most relevant mechanism for immobilizing CO_2, at least in the short term (tens to hundreds of years), which raises concerns for storage permanence until, ultimately, crystallization of the CO_2 begins.

From a broad industrial precedent purview, legal and regulatory parallels for CCS exist, but none fit perfectly to address CCS using deep saline reservoirs. For example: a) CO_2-EOR has been done to maximize oil recovery, but not to sequester CO_2 permanently or for carbon credits; b) natural gas storage has taken place using well-understood reservoirs, but it has not been done in saline aquifers; and c) acid gas injection has been done, but in relatively small volumes. Figure 11 (Logan, 2007) illustrates insight to some of the risks and oversight stakeholders associated with sequestration.

Additional issues of note include:

- CO_2 inconsistent policy, legal, and regulatory oversight
- Safe Drinking Water Act/UIC

- Varying technologies used in capture and transport phases
- Siting – access to and ownership of large reservoirs
- Eminent domain, unitization
- Operation
  - Injection wells
  - Measuring, monitoring and verification
  - Accounting of CO_2
- Injection Well and Site Closure
- Liability/Long-term Injection Site and Field Care



Risk Area/Liability	Large/legal reservoirs; geophysical trespass	Leakage to surface; groundwater, minerals; seismicity; trespass	Leakage to surface; groundwater, minerals; seismicity; trespass	Leakage to surface; groundwater, minerals; seismicity; trespass
Regulatory Authority	Legislature; courts	EPA/UIC; OSHA; state regulator	EPA/UIC; state regulator	Legislature/Congress; EPA; courts
Potentially Responsible Party	Developer	Operator	Operator	Operator; long-term responsible entity
Stakeholders	Surface, mineral owners	Surface, mineral, groundwater workers	Surface, mineral owners	Surface, mineral owners; public; env't

Figure 11 Phases of CCS Liability (Logan, 2007)

With CCS, a long-term perspective needs to be taken in considering post injection issues. These include (Logan, 2007):

- Storage security increases over time
  - Secondary trapping mechanisms
  - Pressure decline
- Time frames are site specific
- Projects can be engineered to enhance trapping
- Monitoring can demonstrate longer term performance
- Eventually, a high degree of assurance will be achieved

As CCS facilities become commercialized, long-term liability issues come into play (Logan, 2007). For example,

- Private entities not likely to develop CCS projects if held responsible "forever"
- Private entities have limited lifetimes
- Need to pass on monitoring and potential remediation responsibility to public entity at some point after closure. Under what conditions? How long?
- Relative requirements of financial responsibility framework (insurance, self-insurance, indemnification, sinking funds, bonds) can create perverse incentives
- Jurisdiction differences between States significant

All liabilities are associated with some level of risk. For CCS, risk has been defined as the probability of a hazard event multiplied by the magnitude of the impacts if it occurs (Anderson, 2017). For geologic storage of CO_2, the impacts of greatest concern are those associated with two types of potential risk events:

1. Leakage of CO_2, displaced fluids, and any mobilized hazardous elements out of the storage reservoir
2. Induced ground motion, including induced seismicity

Impacts could also include contamination of freshwater aquifers and other subsurface natural resources; damage to surface environments and structures; effects on people and animals from extremely high local concentrations of CO_2 in the air; acidification and contamination of oceans and other bodies of water; and damage to ecosystems (Anderson, 2017). Impacts will be greater the higher the concentration of humans and other receptors within the reach of pore space housing the CO_2 plume and the area of elevated pressure, which could extend far beyond the borders of plume migration (IPCC, 2005; Price & Smith, 2008; IEAGHG, 2009; Rutqvist, 2012; NAS, 2013; Birkholzer, Oldenburg & Zhou, 2015); Pawar, Bromhal, Carey, Foxall, Korre & Ringrose, 2015).

LOCAL, NATIONAL & GLOBAL CCS POLICY

Throughout the USA, numerous States have advanced incentives or regulations for CCS. While most individual pieces of legislation do not address all the CCS issues comprehensively, they attempt to provide a patchwork that covers the issues and helps to inform developments in other States (Tomski, Kuuskraa, & Moore, 2012). The USDOE has worked to raise awareness for CCS regulatory and incentivization through ongoing leadership consortiums throughout the USA.

Substantial momentum for large-scale deployment has been built at the local, State, and Federal levels, through engagement with a wide-range of over 400 stakeholders in USDOE's Regional Carbon Sequestration Partnerships. Figure 12 illustrates that for years many States have passed or have considered CCS-related legislation that addresses various implementation issues, ranging from streamlined permitting processes and establishment of roles for various State agencies to clarifying property rights (e.g., pore space ownership, mineral rights, eminent

domain, storage-site unitization); long-term liability provisions; MVA guidelines; financial responsibility; and incentives) (SSEB, 2011).

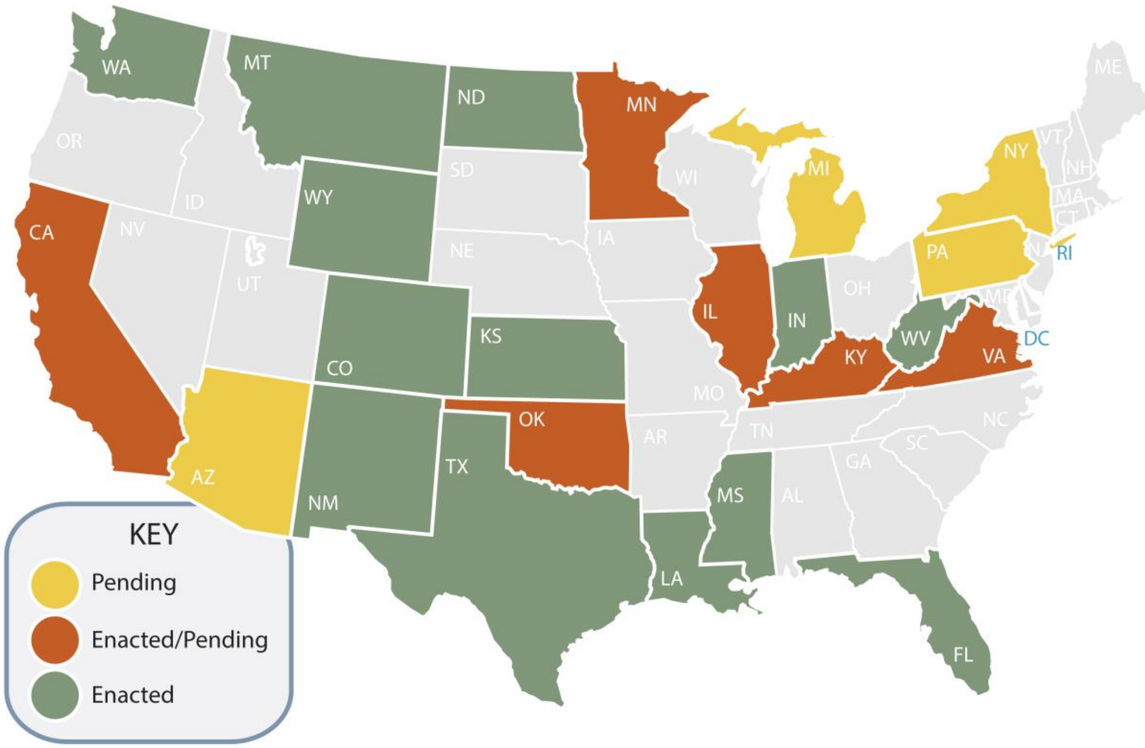


Figure 12 USA State CCS Incentives and Regulation (Source: SSEB, 2011)

Many States have adopted model guidelines for CCS and CO_2 infrastructure development issued by a special task force of the Interstate Oil and Gas Compact Commission (IOGCC). These guidelines were largely based on existing legal and regulatory frameworks governing EOR, or gas-recovery operations (IOGCC, 2005; IOGCC, 2008; IOGCC, 2010; IOGCC, 2011). In 2010, the CCSReg project developed model federal legislation for CO_2-EOR and carbon storage (CCSReg, 2010). The National Enhanced Oil Recovery Initiative (NEORI), a broad coalition of environmental and labor representatives and industry and state officials, has also highlighted model state incentive policies to help realize CO_2-EOR's energy security and economic and environmental benefits (NEORI, 2012).

At the Federal level, the USEPA finalized two closely linked rules in 2010, designed to support and facilitate commercial-scale CCS deployment. The first established a new well classification specifically for geologic sequestration (Class VI) under its UIC Program through the Safe Drinking Water Act (EPA, 2010). The second rule finalized the requirements for CCS (and CO_2-EOR) under the mandatory greenhouse-gas reporting rule (Subparts RR and UU of 40 CFR, Part 98) to enable the EPA to quantify the amount of CO_2 stored underground, along with any surface CO_2 emissions from injecting facilities (Tomski et al., 2012).

In parallel with State and Federal regulatory framework activities, the AARA provided an infusion of funds to support large-scale CCS demonstration projects. In FY 2008, the DOE received \$3.4 billion in ARRA funding for industrial and commercial-scale CCS projects, and an additional \$2.3 billion in annual appropriations. The USDOE's portfolio of competitively awarded, large-scale CCS projects has been supported by \$10 billion USD in total investment (\$3.1 billion from Federal and \$6.9 billion from industry) (Folger, 2017).

STATE OF ILLINOIS LEGISLATION

In August of 2011, the State of Illinois put in place Public Act 097-0534, SB1821 Enrolled, referred to as the "Carbon Dioxide Transportation and Sequestration Act." The legislative purpose addressed the pipeline transportation of CO_2 for sequestration, and enhanced oil recovery. Additionally, it declared CCS to be of public use and service, in the public interest, and a benefit to the welfare of Illinois and the people of Illinois because pipeline transportation is necessary for sequestration, enhanced oil recovery, or other carbon management purposes and, thus, is an essential component to compliance with required or voluntary plans to reduce CO_2 emissions from "clean coal" facilities and other sources. The legislation highlighted the use of CO_2 pipelines as being critical to the promotion and use of Illinois coal and also advance economic development, environmental protection, and energy security in the State.

The Illinois 99th General Assembly also approved HR1501. This legislation called upon the United States Congress to pass, and the President to sign into law, legislation to extend and expand the current Federal tax credit for carbon capture, utilization, and storage under Section 45Q of the Internal Revenue Code.

USA FEDERAL LEGISLATION

The US Senate and the US House of Representatives have seen bills introduced in the last several Congresses that would have tried to foster or shape CCS development in the United States (Folger 2017). This trend has continued in the 115th Congress; several bills have been introduced that would address aspects of CCS. However, the FY2018 Presidential budget request showed a preference for the Government to sponsor R&D activities focused on early-stage research. Early-stage research refers to fundamental research that has a significant degree of scientific or technical uncertainty, which makes it unlikely that industry will invest in significant R&D on its own (USDOE, 2017).

The Senate version of the bill was to fund FER&D at \$573 million in FY2018, \$95 million less than in FY2017, but \$293 million more than the Trump Administration request. In addition, some Members of Congress continued to introduce legislation in the 115th Congress intended to advance CCS. These bills included HR2010, HR2011, HR2296, S843, S1068, S1535, and S1663. Two of these bills, S1663 and S1068, were offered as amendments to tax reform legislation (the Tax Cuts and Jobs Act) under consideration in the Senate Finance Committee (Folger, 2017).

S1535—The Furthering Carbon Capture, Utilization, Technology, Underground Storage, and Reduced Emissions Act

This bill is to amend the Internal Revenue Code of 1986 to improve, expand, and extend the credit for CO_2 sequestration. The S1535 would amend Section 45(Q) of the Internal Revenue Code to increase the tax credit from \$20 per ton to \$50 per ton for capture and permanent

storage of CO_2 and from $10 per ton to $35 per ton for capture and use of CO_2 for EOR. The tax credit amount would ramp up over a 12-year period through 2025, increasing by an inflation factor after that. In addition to CO_2 captured from facilities such as power plants and oil refineries, the credit would be available for facilities that capture CO_2 directly from the atmosphere (direct air capture). The tax credit also would be available for *utilization* of CO_2, such as through bacteria or algae growth or the conversion of CO_2 into a solid material. Facilities and processes that use CO_2 to make materials or otherwise use CO_2 for any other purpose for which a commercial market exists (other than EOR) through utilization would be eligible for the tax credit. As of May 2018, there is an estimated 1% chance of being enacted (S1535, 2018).

S1068—The Clean Energy for America Act

This bill is to amend the Internal Revenue Code of 1986 to provide tax incentives for increased investment in clean energy. The S1068 would make available an investment tax credit for qualified CCS equipment that is installed at an electricity-producing facility and captures at least 50% of the CO_2 emissions at the facility that otherwise would have been emitted to the atmosphere. To qualify, the captured CO_2 would need to be disposed of in secure geological storage. As of May 2018, S1068 had an estimated 1% of being enacted (S1068, 2018).

HR2011 and S843—The Carbon Capture Improvement Act of 2017

Bills HR2011 and S843 are to amend the Internal Revenue Code of 1986 to provide for the issuance of exempt facility bonds for qualified carbon dioxide capture facilities. The HR2011 and S843 would make carbon capture facilities eligible for tax-exempt bonds by amending Section 142 of the Internal Revenue Code. The CCS facility components would be eligible for the tax-exempt bond if the facility captures and stores at least 65% of the CO_2 that otherwise would be emitted to the atmosphere. If the facility captures and stores less than 65% of the CO_2, the percentage of the cost of CCS components eligible for tax-exempt bonds could not be greater than the capture and storage percentage (i.e., if the facility captures and stores 50% of the CO_2, then 50% of the cost of the components would be eligible for the tax-exempt bond). As of May 2018, HR2011 had an estimated 4% chance of being enacted and S843 had an estimated 1% chance of being enacted (HR2011, 2018; S843, 2018).

HR2296—The Advancing CCUS Technology Act

This bill is to increase accountability with respect to Department of Energy carbon capture, utilization, and sequestration projects, and for other purposes. The HR2296 would require the Secretary of Energy to conduct an annual evaluation of every CCS related project that uses DOE funds for research, development, demonstration, or deployment of CCS technologies (including CO_2 utilization technologies). The bill would require the Secretary to determine if the project, whether under contract, lease, cooperative agreement, or other similar transaction with a public agency, private organization, or person, has made significant progress in advancing a CCS technology. Based on the determination of whether progress has been made, the Secretary would make a recommendation to increase funding or would determine that the project has reached its full potential and recommend whether the project should continue. The Secretary would be required to report on the recommendations and make the report available to the public, the Senate Committee on Energy and Natural Resources, and the House Committee on

Energy and Commerce's Subcommittee on Energy. As of May 2018, HR2296 had an estimated 7% chance of being enacted (HR2296, 2018).

HR2010 and S1663—The CO2 Regulatory Certainty Act

HR 2010 and S1663 are bills to amend the Internal Revenue Code of 1986 to enhance the requirements for secure geological storage of carbon dioxide for purposes of the carbon dioxide sequestration credit. The HR2010 and S1663 would amend Section 45Q(d) of the Internal Revenue Code to require that the Secretary of the Treasury, in consultation with the Secretaries of Energy and the Interior and the Administrator of the Environmental Protection Agency (EPA), establish regulations for the geological storage of CO_2. Those regulations would determine compliance for both CO_2 injected for EOR purposes and CO_2 injected for non-EOR purposes (i.e., permanent geological sequestration).

For CO_2 injected for EOR purposes, the bill would consider the CO_2 disposed of (in secure geological storage) if it is stored in compliance with the rules promulgated by the EPA under subpart UU of 40 C.F.R. Part 98, under the Clean Air Act, and subpart C of 40 C.F.R. Part 146, under the Safe Drinking Water Act, to the extent the rules apply to Class II wells. (Class II wells are used to inject fluids associated with oil and gas production, per the Underground Injection Control (UIC) program, authorized under the Safe Drinking Water Act. Class II wells include wells used for EOR.) As of May 2018, HR 2010 had an estimated 9% chance of being enacted and S1663 has an estimated 2% chance of being enacted (HR2010, 2018; S1663, 2018).

CCS in Tax Reform Legislation

In November 2017, the Senate Committee on Finance began considering legislation entitled the Tax Cuts and Jobs Act, which would make changes to the US tax code. Amendments offered to the legislation included S1663 and S1068, the Clean Energy for America Act. However, the tax reform bill considered in the House of Representatives did not contain any provisions to use the tax code for CCS that were under consideration in the Senate.

GLOBAL POLICY FUNDAMENTALS

There are several reinforcing elements of the policy-making process that are critical to accelerate the deployment of CCS. These include (GCSSI, 2017):

- Setting of credible and economy-wide emissions reduction targets, consistent with the aims of the Paris Agreement
- Designing policy to achieve medium-term emissions reductions in a range of sectors and in line with these longer-term targets, combined with measures that meaningfully deal with or compensate those who lose from transitioning to a low-carbon future
- Explicitly including CCS in national climate action plans or similar flagship policy statements, which either implicitly or explicitly acknowledge how CCS can play a role alongside other low-carbon technologies
- Securing policy certainty via a government commitment that has been demonstrated to extend beyond political cycles and to be resilient to conflicting political demands

- Establishing (region-relevant) public/private business models that better manage risk allocation between the capture, transport and storage elements of the CCS chain, thus reducing overall risks
- Devoting special attention to accelerating investment in storage exploration and characterization, in view of the long lead times for development in certain regions

CONCLUSIONS & RECOMMENDATIONS

While CCS development and demonstration cost has been a deterrent for public and private investment, there are grounds for optimism that CCS deployment may accelerate after 2020. Growing demand for the beneficial reuse of CO_2 for EOR should drive CCS forwards during this decade and help to demonstrate the technology, in conjunction with large government grants. While oil prices are currently considered low, oil prices above \$100/bbl (barrel) have tended to boost CO_2 contract prices above \$30/tCO_2, greatly improving CCS-EOR economics (Folger, 2017).

Globally, growing users of CCUS technology are having significant impact. For example, China is rapidly driving down the cost of capture, having openly expressed the ambition to build capture-only coal power plants for its own needs and to export low-cost capture technologies. The levelized cost of electricity from coal-fired power plants with CCS, using either post- or pre-combustion technology, could decrease by 14%-21% after the first 100 GW are installed.

Closing the gap between CCS rhetoric and CCS technical progress is critically important to global climate mitigation efforts. Developing strong international cooperation on CCS demonstration with global coordination, transparency, cost-sharing and communication as guiding principles will facilitate efficient and cost-effective collaborative global learning on CCS, will allow for improved understanding of the global capacity and applicability of CCS, and will strengthen global trust, awareness and public confidence in the technology (de Conick, et al., 2009).

The use of CCS technology is increasingly recognized as having critical potential to mitigate climate change (IPCC, 2005; IEA, 2008) and it is the only technology that reduces carbon emissions from coal-fired power plants, while coal is at present the predominant fuel for electricity and responsible for no less than 40% of global CO_2 emissions. About 100 GW of additional coal-fired power capacity is currently built every year, and the use of coal is projected to increase in the decades to come (IEA, 2008). It has been suggested that confidence in CCS could be a pre-requisite for a global agreement on large-scale CO_2 emissions reductions (Gibbins & Chalmers, 2008). CCS technology can also be considered in combination with renewable energy, such as biomass-fired power plants, where it can theoretically provide carbon-negative electricity generation that directly lowers carbon dioxide concentrations in the atmosphere (IPCC, 2005).

It is well-documented that CCS is considered to be a crucial part of world-wide efforts to combat global warming by reducing greenhouse gas emission (Leung et al., 2014; Gibbins & Chalmers, 2008). It was estimated that about 100 CCS projects need to be implemented by 2020 and over 3000 by 2050 in order to reach the goal of restoring the global temperature by 2^oC (IEA, 2009). Although some of the technologies regarding CCS have been proven,

comprehensive commercial projects involving large-scale CCS are lacking. The IEA (2012) pointed out a number of barriers of implementation of CCS:

- Lack of a market mechanism/incentive that is sufficiently large and long term enough to reward an entity with carbon reduction using CCS technologies
- No mechanism to penalize those major CO_2 emitting sources
- Inadequate legal framework allowing transport and geological storage of CO_2 for both inland and offshore storage
- Most of the current storage practices/demonstration projects are related to EOR or ECBM, which are more financially viable but have limited CO_2 storage capacity as compared to ocean and deep saline aquifers
- Demonstration in the latter two technologies need to be enhanced

The UKDECC (2013) identified a series of key points through the CCS chain to make its development an economically feasible solution:

- Identification of reliable storage sites with capability of switching between the sites in case a backup is needed
- Use clusters of storage sites as “hubs” where different CO_2 sources can be delivered thus reducing the cost by sharing the infrastructures
- Develop a large-scale network of pipelines
- Scaling up the CCS demonstration projects
- Reduction in the energy penalty associated with capturing CO_2 from powerplants
- Assuring financial stability to the CCS projects by a regulatory and policy framework
- Explore the effectiveness of EOR in off-setting part of the costs associated with CCS
- Identify CO_2 sources beyond power generation which can be used for CCS.

There are no major technological barriers to the capture and geological storage of CO_2 for existing operation but noted that CCS is an energy intensive process that lowers the overall efficiency of the concerned energy generating systems. It is inevitable that the costs, both capital and operation, involved in plants equipped with CCS are much higher than those without capture due to the reduction inefficiency and additional capital cost for installing the capture, transport and injection facilities.

The high cost of CO_2 capture, particularly for dilute streams like those from gas-fired power plants and industrial combustion processes, is the major challenge of CCS (Watson & Bachu, 2009). Page, Williamson, and Mason (2009) compared the energy for CCS and efficiency penalty for different types of power plants and found that there are wide variations even for the same type of power plants. However, they deduced that part of the costs associated with CCS could be offset by using the CO_2 for economically productive application. For example, EOR/ECBM in the USA is forecasted to enable the ongoing storage of CO_2 generating revenue, which should far exceed the CCS costs of implementation.

It is important to recognize that CCS is not a single technology but consists of sets of technological components associated with capturing, transporting and storing CO_2 deep

underground. While many of the individual components of a CCS system have already been used in other industrial applications, the technological maturity of different CCS components varies. Progress on the technological maturity of the various components has been slow over the past five years; only in oxyfuel combustion has there been significant recent progress with the opening of a CO_2 capture demonstration plant with aquifer storage near Berlin, Germany.

Despite limited progress and variation in technological readiness among the different components, there is widespread optimism about the technical feasibility of all components of CCS and about the integration of the components. The critical obstacle at this point is that CCS in the power sector has not yet been repeatedly demonstrated at commercial-scale, therefore technological risks, which enhance the already significant cost barrier, remain a clear near-term barrier to implementation.

A lack of funding for the large-scale demonstration of technologies is a well-recognized problem in technology innovation. After a successful R&D phase, public funding is often reduced, while private funding for application of the technology is still seen as uneconomical or too risky. The cash flow for the new technology dries up, and the ensuing “valley of death” looms (Murphy & Edwards, 2003). This pattern of difficulty at the demonstration phase can be identified in many emerging technologies, but is particularly pronounced in large-scale, capital intensive technologies such as CCS.

Most global emission projections are currently suggesting that large-scale implementation of CCS is required to achieve deep reductions in emissions within the next few decades. Ten years ago, the IEA World Energy Outlook (2008), for example, showed that significant CCS deployment is needed from 2020 to 2030 to achieve a 450 ppm instead of a 550 ppm stabilization scenario. The lack of commercial-scale CCS demonstrations put in place in response to these now aged projections highlight the urgent need to accelerate CCS as an emerging technology to readily achieve global technology transfer before 2030.

Given the prominent role that CCS is now taking in considering global attempts to attain climate mitigation goals in terms of the deep reductions needed in the 2020-2030 timeframe (IPCC, 2014), it is essential that CCS does not fall into this “valley of death” trap, that the process of technological learning is accelerated, and that costs are reduced. Fortunately, it is widely acknowledged that demonstration of various different configurations of a full CCS system is needed.

The need for multiple commercial-scale demonstrations remain necessary to achieve a viable technology transfer for commercial purposes. Numerous benefits of international cooperation in energy technology development have been identified in previous studies (PCAST, 1999; NCEP, 2004). Based on such studies, four opportunities for international cooperation on CCS demonstration were delineated: (1) accelerating learning, (2) globalizing learning, especially in countries that might not independently invest in the technology, (3) expanding social awareness of and discourse about the acceptability of CCS, and (4) ensuring consistent, safe implementation of CO_2 storage. For CCS, these benefits can be maximized through a coordinated global policy and program that facilitates the planning, implementation and learning from CCS demonstration projects throughout the world.

As commercial-scale demonstration is a limiting factor in global acceptance of CCS, several guiding principles for CCS demonstration are include:

- Global coordination: the initiative should enable a variety of CCS technologies to be demonstrated in various contexts and countries
- Transparency: the initiative should ensure open information availability and exchange between countries to promote broad global efficient learning on CCS
- Cost-sharing: the initiative should set up a cost-sharing structure that pools global demonstration funds and reallocates them efficiently to allow for fast access of emerging economies to CCS technology and demonstrations
- Communication: the initiative should design mechanisms to support demonstration projects that engage broad and different types of stakeholders and that incorporate education and outreach efforts. Open and effective communication with stakeholders, the media and the general public should be integral, and the cooperation should heed principles of risk communication, and support an open dialogue on CCS with all involved

Looking beyond 2020, more stringent carbon policies will be required to develop CCS beyond upstream oil and gas and at the scale needed to tackle climate change. CCS is widely recognized as a viable technology for climate change mitigation, as CO_2 emissions are being locked-in by existing plants. In addition to public funding and a more robust carbon-pricing system, public and private sector actions could contribute to CCS's wider adoption by:

1. Implementing commercial-scale projects for Leveraging CCS-EOR projects
2. Implementing focused regulation governing long-term investments
3. Exploring new business models to assist the formation of partnerships in integrated CCS projects
4. Enacting global Climate Change Policy promoting CCUS
5. Establish financial incentives for viable ROI for CCUS projects (e.g., carbon credits, government sponsored projects
6. Implement global education and outreach to address societal issues/concerns

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