CONFERENCE PROCEEDINGS

Coupling CO_2 Capture and Storage with Coal Gasification: Defining "Sequestration-Ready" IGCC

Jennie C. Stephens, Energy Technology Innovation Project,
Harvard University

FOURTH ANNUAL CONFERENCE ON CARBON CAPTURE AND SEQUESTRATION DOE/NETL
May 2-5, 2005

Abstract

Carbon dioxide (CO_2) can be separated and captured more efficiently and at a lower cost from an integrated gasification combined cycle (IGCC) coal generation power plant than from a conventional pulverized coal power plant. This advantage for addressing CO_2 emissions is one important reason that the National Commission on Energy Policy has recently called for increased federal funding to encourage the construction of IGCC power plants that are "sequestration-ready". An important outstanding policy question is to what extent initial commercial IGCC power plants supported by federal funds should be required to prepare for, pre-invest in, or install and operate CO_2 capture equipment, i.e. what does the term "sequestration-ready" mean for an initial fleet of IGCC power plants? Adding CO_2 capture capabilities to an IGCC power plant is not a simple end-of-pipe modification, so planning for the addition of this capability is appropriate. Without any current regulatory or economic incentives for power plants to capture and store CO_2, however, the appropriate extent of this sequestration-ready requirement is unclear. This paper assesses a spectrum of progressively more involved potential requirements for incorporating consideration of CO_2 capture and storage technology in the design of new IGCC power plants.

1. Introduction

Among the various environmental concerns associated with coal-fired power plants, CO_2 emissions are viewed by many as the most critical because CO_2 is the dominant greenhouse gas contributing to climate change. Coal combustion currently produces 34% of the global emissions of CO_2, and coal fired power generation emits more CO_2 per unit of energy than any other power generating process. Although the US has not yet imposed regulatory limits on CO_2 emissions while other industrialized countries around the world have, growing concern over the impacts of climate change has resulted in growing anticipation of US CO_2 regulation. For coal to remain a major source of electricity generation within a CO_2 constrained world, CO_2 capture and storage (CCS) technologies will have to be deployed in conjunction with coal fired power plants. The ease and efficiency of capturing CO_2 from a coal-fired power plant is dependent on the coal technology, and the 50-70 year lifetimes of power plants means decisions made now about what type of coal-fired power plant technology to build will lock-in specific characteristics related to future CO_2 capture capability.

Integrated gasification combined cycle (IGCC) is the coal-fired power plant technology that provides the greatest potential for minimizing emissions associated with using coal to produce electricity. Rather than generating electricity from the heat produced from burning coal, as is done in conventional coal combustion steam-electric power plants, IGCC power plants rely on established chemical engineering technologies to turn the solid fuel into gas (known as syngas). Before the syngas is burned to produce electricity, impurities can be removed from the fuel more effectively and efficiently than can be accomplished in conventional combustion coal plants where post-combustion clean-up is required. This capacity for pre-combustion clean-up of pollutants is one of the technology's primary advantages over conventional coal combustion approaches. Lower cost and more effective removal of currently regulated pollutants, including particulates, sulphur dioxide (SO_2), and mercury (Hg), is made possible with IGCC, and the technology also allows for lower cost separation and capture of carbon dioxide (CO_2), the dominant greenhouse gas contributing to climate change.

Despite its environmental superiority, IGCC technology is not currently commercially competitive due to higher costs of building an IGCC plant and the additional risk of investing in a technology without an operational history (Campbell et al., 2000; EPRI, 2005; NETL, 2002). Although a handful of IGCC demonstration plants are in operation around the world and several major players in the coal industry have recently announced plans to build IGCC power plants (pending regulatory and financing approval), operational experience from commercial scale facilities is needed for the technology to become competitive.

The National Commission on Energy Policy, a diverse bipartisan group of energy leaders and experts, included in their recent recommendations for U.S. energy policy increased federal funding to encourage the construction of IGCC power plants that are "sequestration-ready" (National Commission on Energy Policy, 2004). This concept of building IGCC power plants that are capable and ready to capture and store CO_2 is also implied in other recent proposals for government support of the deployment of an initial fleet of IGCC power plants (Rosenberg et al., 2004). Given that the relative ease and efficiency of capturing CO_2 from IGCC coal plants is the technology's most valuable characteristic, an important outstanding policy question associated with current efforts to promote IGCC technology is to what extent initial commercial IGCC power plants supported by a federal subsidy should be required to prepare for, pre-invest in, or install and operate CO_2 control equipment.

This paper has been developed to outline potential requirements that could be included in the term "sequestration-ready" IGCC. The paper first reviews the technical and economic details associated with adding CO_2 capture technology to the design of an IGCC power plant and then identifies and explores several potential CO_2 capture and storage requirements with varying degrees of integration that could be included in a federal financing plan designed to support IGCC deployment.

2. Technical Details Associated with Coupling IGCC and CCS

Producing power with IGCC technology begins with the conversion of solid fuel (coal, biomass, pet coke, etc) to gas (synthesis gas or syngas) (See Figure 1). The coal is gasified in a gasifier with steam and oxygen; different gasifier designs perform the gasification process at different temperature and pressure conditions (the Texaco/GE gasifier operates at a higher pressure than the E-gas gasifier for example). After gasification the syngas is cooled down generating steam that is sent to the steam turbine to generate some electricity. It is at this point, before the syngas goes to the gas turbine to generate additional electricity, that pre-combustion chemical processes can be inserted to separate and capture CO_2 and other pollutants from the syngas. Once the CO_2 is separated, the gas can be transported to a storage location.

Adding CO_2 capture capability to an IGCC power plant is not a simple end-of-pipe modification; in addition to adding the CO_2 capture equipment changes in other components are required. The removal of CO_2 from the syngas prior to combustion alters the composition of the gas to be burned, increasing the hydrogen content, which changes the design requirements for the gas turbine. In addition, the CO_2 capture process adds complexity to the optimal design of desulphurization and other gas clean-up processes and increases both energy consumption and the amount of coal required to generate the same amount of electricity. For these reasons, an IGCC plant built without consideration for CO_2 capture technology designed to produce power at a minimum cost and maximum efficiency will be different than an IGCC plant designed to incorporate CO_2 capture technology whether the initial plant design includes CO_2 capture equipment or includes measures to prepare for anticipated installation of CO_2 capture equipment in the future.

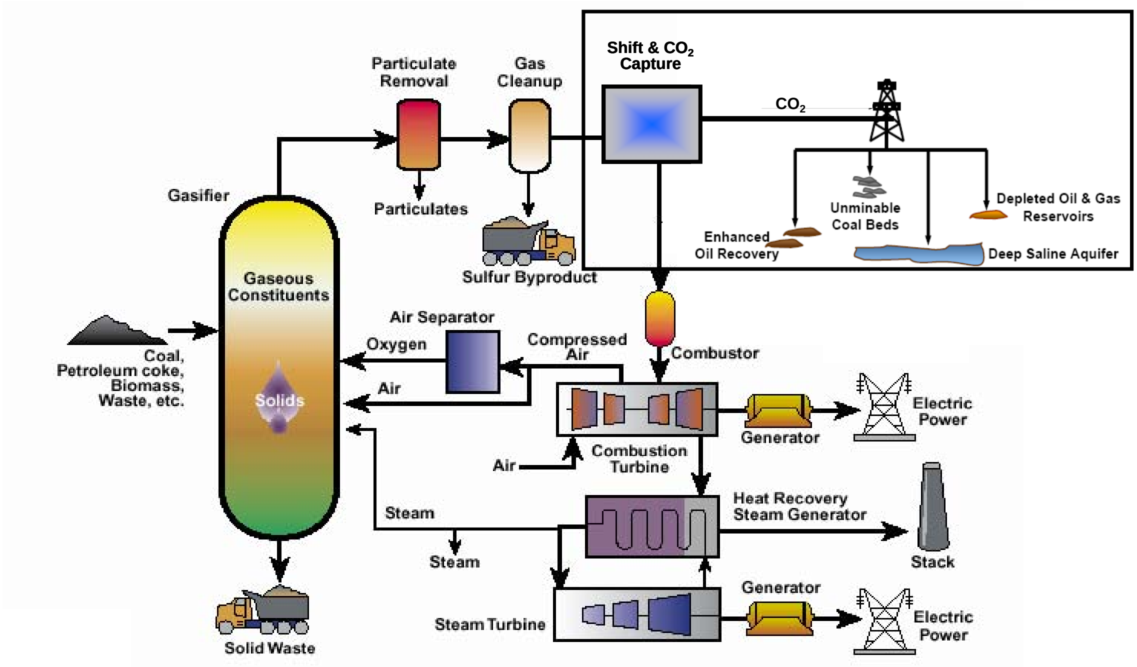

Figure 1 – Schematic representations of an IGCC coal-fired power plant. The section inside the box in the upper right includes the CO_2 capture and storage (CCS) components. This figure demonstrates that adding CCS is not an "end-of-pipe" retrofit, but due to the integrated cyclical design would require modifications of several components. (From Rosenberg, 2004)

Although none of the existing IGCC power plants currently capture CO_2, decades of experience has been accumulated with CO_2 capture technology in other applications. CO_2 is captured in several industrial processes including the production of hydrogen, ammonia, and synthetic liquid fuels as well as in the purification of natural gas (Kohl and Nielsen, 1997). Although the CO_2 removed from the gas streams in these industrial processes is generally vented to the atmosphere, the same technology, relying on physical absorption of the CO_2 onto a solvent, can be scaled up to capture CO_2 from an IGCC power plant that can then be transported to an underground storage location. The quantity of CO_2 separated from any one of these industrial processes would be much less than 1 Mt CO_2 per year, while a single 1000 MW IGCC plant would emit about 8 Mt CO_2 per year, so demonstration of the scaling up of these processes to the power plant scale is required.

Three major technological components need to be added to a basic IGCC plant to allow for the separation and capture of CO_2: (1) the shift reactor to convert the CO in the syngas to CO_2, (2) the process to separate the CO_2 from the rest of the gas stream, and (3) a compressor to reduce the volume of separated CO_2 before it can be transported. Additionally, other components will require modification, including the gas turbine that will have to be capable of operating with H_2-enriched gas streams, the timing of the sulphur removal process within the system may be moved to co-capture CO_2 and H_2S, and some scaling up will be necessary to accommodate the larger quantity of coal required to generate the same amount of power as an IGCC plant without CO_2 capture. The additional complexity associated with the additional CO_2 capture components and their integration will also increase the level of operational risk, as malfunctions or disruptions in the CO_2 capture system could impact the productivity of the entire plant.

2.1 The Shift Reactor

The first step in separating and capturing CO_2 from the syngas, which is made up predominantly of carbon monoxide (CO) and hydrogen (H_2), is to convert the CO into CO_2. This is done by reacting the CO with steam in a catalytic reactor in a process known as the water gas shift reaction. When the syngas is funneled into the reactor (or a series of reactors) with steam, the following reaction occurs:

$$CO + H_2O_{(g)} \rightarrow H_2 + CO_2. \tag{1}$$

This reaction is exothermic, so the heat produced contributes to the power generated in the steam turbine.

2.2 The Absorption/Separation Unit

After CO is converted to CO_2 and H_2 in the shift reactor, CO_2 would be separated from the rest of the gas by physical absorption. CO_2 separation in industrial processes is generally achieved using one of two methods: (1) chemical absorption with solvents including MonoEthanolAmine MEA using heat induced CO_2 recovery, or (2) physical absorption using solvents including Selexol (dimethly ether of polyethylene glycol) with pressure induced CO_2 recovery. Chemical absorption requires more energy than physical absorption because the chemical bonds are stronger than the weak binding of the CO_2 in physical absorption. While chemical adsorption is the separation method of choice for capturing CO_2 from flue gas from a conventional coal-fired power plant where the CO_2 concentrations are low (9-14%) and the CO_2 partial pressure is low, but the less energy intensive physical absorption method is effective in an IGCC pre-combustion CO_2 separation process because of the high operating pressures and relatively concentrated CO_2 stream (30-32% CO_2 by volume). In physical absorption, once the CO_2 has adsorbed to the solvent, regeneration of the solvent occurs by reducing the pressure in one or more stages until the CO_2 is released. The only energy required for this step is that needed to pressurize the gas. Among the commercially available physical absorption solvent processes, Selexol (dimethly ether of polyethylene glycol) and Rectisol (methanol) are the most commonly considered, but R&D on other potential solvents with different temperature and pressure requirements is ongoing (IEA, 2004).

2.3 The Compressor

The third additional component is the compressor required to reduce the volume of the CO_2 gas to allow for more efficient and cheaper transportation of the gas to a storage location. When CO_2 is compressed to its dense phase, the volume of gas can be reduced to about 0.1% of the gas volume at standard conditions of pressure and temperature. Compressing gas is energy intensive, so this part of the CO_2 capture system adds significantly to the overall operating costs. Projected capture costs generally include the cost of compressing CO_2 to a pressure suitable for pipeline transport (typically ~14 MPa), but depending on the requirements for transport and the storage location, additional compression could be required (the CO_2 pressure required for storage is correlated with the depth of each specific storage reservoir).

2.4 The Gas Turbine

The gas turbine is the most critical component of an IGCC plant that would require modification if an IGCC plant were to include CO_2 capture technology. The removal of CO_2 from the syngas alters the composition of the syngas to be burned in the gas turbine, creating a CO_2-depleted and H_2-enriched gas. Gas turbines are designed for specific gas compositions, so the capability of gas turbines to accept H_2-enriched gas has been viewed as a potential obstacle to the integration of CO_2 capture technology with IGCC. Most of the new gas turbines (i.e. GE F series), however, are capable of operating with H_2-enriched fuel; several elements, including the fuel control skid and the combustors, would have to be designed differently or retrofitted to accommodate the H_2-enriched fuel associated with CO_2 capture (Shilling, 2004). In order to minimize NOx emissions, H_2 concentrations in the gas entering the turbine would likely be kept below 65% because of hydrogen's high flame temperature. NOx emissions are correlated with flame temperature (Cook et al., 1995), so to keep the temperature down any fuel with a concentration above 65% H_2 would likely be diluted with either nitrogen or steam to get below that percentage.

A challenge for gas turbines operating with gas with high H_2 concentrations is that turbine lifetimes are shortened by the lower BTU content of the fuel that results in higher mass flow rates through the turbine and by the higher water content and the associated increase in heat transfer. Experience operating gas turbines with high H_2 concentrations (52-95% by volume) has been reported (Shilling and Jones, 2003), but this experience is primarily with refinery gas used in older, lower temperature gas turbines. Recent development and testing of current gas turbine technology with H_2 rich gas has, however, increased confidence in turbine performance with high H_2 concentrations (Shilling, 2004).

2.5 Sulphur Removal

In addition to the gas turbine, another major modification associated with adding CO_2 capture would be the sulfur removal process. During gasification, the sulphur contained in coal is converted to H_2S (hydrogen sulfide) and COS (carbonyl sulfide). In a typical IGCC design without CO_2 capture COS is hydrolyzed to H_2S in a catalytic bed at about 200^oC, and then H_2S is removed from the syngas using a physical solvent, often Selexol, achieving high removal efficiencies up to 99% . A sulphur recovery unit then uses heat to oxidize the H_2S to produce elemental sulfur. Given that the same physical absorption process and the same solvent, Selexol, extract both H_2S and CO_2 from syngas several different sequences for H_2S removal are possible within a plant that is also capturing CO_2. One option would be to keep the H_2S and CO_2 removal completely separate by placing the H_2S removal system before the water gas shift reactor. Another option would be to install a Selexol unit that could co-capture both CO_2 and H_2S. This option eliminates the need for the COS hydrolyzation unit because most COS is converted to H_2S in the water-gas-shift reactor (Chiesa et al., 2005).

A recent study estimated that co-capture of H_2S and CO_2 could increase efficiency of the plant and reduce overall costs up to 20% (IEA, 2003). Co-capture eliminates the need for the energy required for the sulphur recovery unit and simplifies the overall process. The estimated cost savings of co-capture, however, are associated with corresponding cost increases in transport and storage; the presence of H_2S increases the volume of gas needed to be compressed, transported and stored. In addition, the H_2S reduces pipeline capacity and also requires more advanced and expensive anti-corrosion materials and coatings. The presence of H_2S in the gas stream at the storage stage could result in the gas stream being classified as hazardous, which would impose different requirements for injection and disposal in an underground storage formation than if the gas were pure CO_2. Although uncertainties remain about the impacts of co-storing CO_2 and H_2S in underground geologic formations, this does not seem to be technically infeasible given the experience with regulated underground injection of waste acid gas with high concentrations of H_2S (Wilson et al., 2003). Whether or not an IGCC plant with CO_2 capture technology is set up to co-capture CO_2 and H_2S has direct implications for several other components; with co-separation the shift reactor, in particular, would have to be effective with "sour" gas, i.e. gas that has not yet been desulphurized.

Another option would be to have two adjacent but separate Selexol units after the water-gas-shift reactor; the first designed to separate H_2S and the second targeting CO_2. To prevent CO_2 removal in the H_2S Selexol unit, the solvent will have to be pre-loaded with CO_2 in a previous step (EPRI, 2000).

2.6 Scaling Up

Another set of modifications in an IGCC with CO_2 capture would involve scaling up the plant to achieve the same amount of power output. Adding the additional components for CO_2 capture increases both energy consumption reducing the electricity produced, and also increases the amount of coal required to generate the same amount of electricity.

2.7 CO_2 Transportation and Storage

Once CO_2 is captured and compressed, the CO_2 needs to be transported to an appropriate storage location. Injecting captured CO_2 into underground reservoirs, including depleted oil and gas reservoirs as well as saline aquifers, has emerged as the most promising potential storage strategy (Anderson and Newell, 2004; Bachu, 2003; Holloway, 1997; IEA, 2004; Stevens et al., 2001). A handful of large-scale underground CO_2 storage demonstration projects are in existence, and CO_2 has been injected underground for Enhanced Oil Recovery (EOR) for decades (Anderson and Newell, 2004; Friedmann, 2003; Wilson et al., 2003). These EOR experiences are also associated with hundreds of miles of CO_2 pipelines for transport. If an IGCC plant were to be retrofitted for CCS, the proximity to an appropriate storage location will determine the extent and associated cost of transporting the CO_2.

3. Potential Requirements of a "Sequestration-Ready" or "CCS-Ready" IGCC

Although various policy proposals associated with supporting the deployment of IGCC specifically mention or allude to the capability of IGCC power-plants to capture and store CO_2 in the future, the terms "sequestration-ready" or "CCS-ready" have not been defined. Several potential requirements for a "CCS-ready" IGCC plant could be considered for plants built today with anticipation for future retrofit installation of CO_2 capture technology and future CO_2 storage. This discussion assumes that the costs associated with initiating CO_2 capture and storage can not currently be justified privately and are not going to be supported with public funds, yet that if public funds are going to support an initial fleet of IGCC plants the technology's primary advantage, the capability to capture CO_2 for storage, must be incorporated to some degree.

3.1. Conceptual Plan

A minimal requirement for a "CCS-ready" IGCC power plant would include a conceptual plan for a future retrofit. This requirement would not require any actual changes to the IGCC plant to be initially built, but it would require early consideration of how a future retrofit would occur. This requirement would require that future CO_2 capture capability has been considered in the design of the current plant, but would not add any significant additional initial costs to the plant.

3.2 Additional Size Requirement – Preinvestment

An additional requirement that would require a larger pre-investment in anticipation of future CCS technology could involve allocating sufficient additional space in the plant to accommodate the additional CO_2 capture equipment. This requirement would also involve preparing for the resizing of some components that would have to occur with a future retrofit to maintain the same level of power output.

A recent study assessing the costs associated with preparing for a future CO_2 capture retrofit by pre-investing in additional space and resizing, estimated an increase in upfront costs of about 5% (EPRI, 2003). This study, which included oversizing the initial fleet of plants and leaving additional physical space for the shift reactor, absorber and compression units as the pre-investment requirements, estimated that a 5% increase in initial costs would increase the cost of electricity by about 3-6%. They also predicted that this level of pre-investment would reduce the costs of a future retrofit; the cost of electricity increased 22-28% when retrofitted compared to anticipated cost of electricity increase of 30-43% when CO_2 capture is added without pre-investment.

3.3 Identification of an Appropriate Storage Location

Another potential requirement could be for a specific appropriate underground storage location be identified and characterized for a repository for the CO_2 to be captured in the future. Such a requirement could limit appropriate locations for IGCC plants, however, economies of scale and geographic variation in pipeline costs are such that there is no definitive distance over which one can claim that transportation costs are too expensive (Bradshaw, 2004, personal communication). The distance between the storage location and the power plant would vary, therefore, depending on the proximity of the power plant site to appropriate geologic formations, but this requirement would require consideration of the feasibility and costs associated with building a CO_2 pipeline to the storage location.

This requirement would add several major additional factors into the power plant location process. Traditional factors included in determining power plant location include proximity to load, access to fuel, water availability, environmental and social consideration, as well as site specific factors including space and layout. This requirement would add a requirement for identification and characterization of a specific potential storage location, for consideration of the feasibility of transporting the CO_2 to that location, and for considering the potential for shared CO_2 pipelines and storage locations.

3.4 Installation of CO_2 Capture Equipment Without Full Integration

The size and complexity of power plants means that there are major inefficiencies associated with optimizing an initial design and construction of a power plant to run one way and then at some point later retrofitting that plant to run in a very different way. In addition there is considerable risk associated with investing for preparedness for potential future retrofits when there is large potential for technological changes in both the IGCC technology and the CO_2 capture technology (Davison et al., 2004). The options described below avoids these inefficiencies and risks by assuming some way to cover the additional costs associated with installing CO_2 capture equipment from the onset. Due to the significant costs of installing CO_2 capture equipment, additional government incentive, either financial or regulatory, might be required for these options to be realized.

3.4.1 Require a Slipstream for CO_2 Capture Demonstration

One option that would limit the additional upfront capital costs but allow for relatively easy adoption of CO_2 capture technology demonstration is to require IGCC power plants to design capabilities to divert a slip stream of the syngas before the gas turbine to be go through the CO_2 capture process. This requirement would allow the plant to be built and optimized without CO_2 capture technology, but would allow for the possibility of getting some of the needed operational experience with CO_2 capture if additional funding to demonstrate CO_2 capture were provided. The major advantage of this option is that it sets-up a near term potential opportunity for gaining experience with CO_2 capture technology without taking the risk of pre-investing a lot of money to prepare for a technology that may change considerably between the time that the plant is built and the time that it will be advantageous to install CO_2 capture technology. The costs associated with installing the CO_2 capture equipment to separate the CO_2 in the slip stream would still be high, but this plan provides a starting point for requesting additional funds to support the separate CO_2 capture component of the project. While the bulk of the capital costs of installing the CO_2 technology are likely to be quite comparable to that when the CO_2 capture equipment is incorporated into the IGCC plant, the smaller quantities of gas would reduce the scale of the required equipment which would lower the costs. In addition, the lack of integration and comparative simplicity of only capturing CO_2 in a separate slip stream would reduce overall costs. While this option attempts to satisfy, to some degree, the needs for demonstration of CO_2 capture technology, the slipstream approach does not provide the valuable and necessary operating experience with CO_2 capture technology integrated into an IGCC power plant.

3.4.2 Require Installation of Equipment Without Full Utilization

Given the inefficiencies associated with building a plant one way but anticipating a retrofit sometime in the future, another option would be to require the installation of CO_2 capture equipment but limit the immediate utilization of the CO_2 capture components. This option allows the initial construction costs to be optimized for capture, but the full energy penalty associated with actually capturing the CO_2 is not realized. Given the high level of cycling and integration in an IGCC power plant with CO_2 capture, reducing the utilization of the CO_2 capture components may be complicated and reduce the viability of this approach. Installing equipment including the shift reactor and the sorption units but then postponing their use may have a similar level of difficulty as does preparing for a future retrofit at some point in the future. There is uncertainty and technical debate about the relative difficulty and cost of adding the shift reactor and the sorption unit during a retrofit versus installing these components initially and not actually capturing the CO_2.

Compressing the CO_2 gas to prepare for transport to a storage location is one of the most expensive parts of CO_2 capture, so to reduce operating costs but still gain operational experience with separating the CO_2 all of the CO_2 separation equipment except the compressor could be installed and operated. Given the extensive application of gas compression, demonstration of CO_2 compression is not critical. If the near-term goal of accumulating operational experience with CO_2 capture technology was the priority, and the initial funding to cover the capital costs were supplied, this option could be viable. This option also provides a set-up for going farther and actually compressing, transporting and storing the CO_2 if and when there is support to do so.

4. Conclusions

In addition to the specific requirements mentioned in each of the sections above, multiple variations within each category are possible. If the U.S. government is going to provide a subsidy to promote the deployment of IGCC power plants that are "sequestration-ready," policy-makers are going to have to define the specific requirements. A complex array of political, economic and technical uncertainties will be considered in determining the appropriate definition.

One of the biggest uncertainties that will influence opinions on what "sequestration-ready" should mean is the likely timeframe in which a cost of emitting CO_2 to the atmosphere will be imposed. While many are anticipating restrictions on CO_2 emissions that will generate a cost of emitting CO_2 within 5-10 years, some do not anticipate any CO_2 regulations in the U.S. The minimal requirements involving developing a conceptual plan of a future retrofit without actually requiring any actual changes to the initial plant design is likely to be favored by those who view a long time before a real cost will be associated with emitting CO_2, while the more stringent requirements that will involve a significant level of pre-investment will be viewed more favorably by those who anticipate a CO_2 cost in the next few years.

This discussion of the term "sequestration-ready" or "CCS-ready" highlights the need for efforts to couple the deployment of IGCC with actual CCS demonstration. The size and complexity of power plants means that there are major inefficiencies associated with optimizing an initial design and construction of a power plant to run one way and then at some point later retrofitting that plant to run in a very different way. In addition there is considerable risk associated with investing for preparedness for potential future retrofits when there is large potential for technological changes in both the IGCC technology and the CO_2 capture technology. Due to the significant costs of installing CO_2 capture equipment and transporting and storing the captured CO_2 in the absence of a CO_2 regulating regime, additional government provided incentives, either regulatory or financial, beyond the support for IGCC deployment, would be required for coupled, integrated projects incorporating both IGCC and CCS.

Acknowledgements

The author thanks Bill Rosenberg, Mike Walker, John Holdren, Henry Lee, Guodong Sun, and Kelly Sims Gallagher of the Energy Technology Innovation Project for guidance on this project. In addition, discussions with many including David Hawkins, Bob Williams, Tom Kreutz, Rob Socolow, and Norm Schilling contributed to this work. Financial support for this project is gratefully acknowledged from the Energy Foundation, the Hewlett Foundation, the Packard Foundation, the Winslow Foundation, and the endowment of the Belfer Center for Science and International Affairs at the Kennedy School of Government at Harvard.

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