Royal Institute of Technology

Division of
Energy Systems Analysis

Working Paper Series

DESA/12/8

Energy Security and Carbon Capture and Storage

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Introduction

The First Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) expressed concerns about anthropogenic greenhouse gas (GHG) emissions and their impact on climate stability. In 1992, this concern led the world community to create the United Nations Framework Convention on Climate Change (UNFCCC). The ultimate objective of that Convention is to achieve stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.

Although what constitutes dangerous interference has yet to be defined, it is obvious from IPCC's Third Assessment Report ("Global average temperatures and sea level are projected to rise under all scenarios") that even a stabilization at the twice the pre-industrial industrial level of 280 ppmv would require drastic GHG emissions reductions to, say, 20-30 percent of current annual emissions.

Carbon dioxide (CO_2) accounts for approximately 70 percent of anthropogenic GHG emissions. CO_2 emissions arise from a number of sources, but predominately from fossil fuel combustion in the power generation, industrial, residential and transport sectors. "Emissions of CO_2 due to fossil fuel burning are virtually certain to be the dominant influence on the trends in atmospheric CO_2 concentration during the 21st century" (IPCC, 2001).

Technological options for reducing net CO_2 emissions to the atmosphere include:

Rational energy use. Reducing energy needs through efficiency improvements of energy production and utilization throughout the energy system and shifting to less energy-intensive economic processes.

Switching to less carbon intensive fossil fuels. Using natural gas instead of coal reduces emissions by virtue of the gas' lower carbon content per unit of energy. In addition, gas allows the use of high efficiency combined cycle technology. The net result is lower CO_2 emissions per kWh of electricity generated.

Increased use of renewable sources. Technological advances and technology learning offer new opportunities and lower costs for renewable technologies for both off-grid and grid applications.

Increased use of nuclear power. Nuclear energy could replace fossil fueled electricity generation in many parts of the world.

Carbon sequestration: Enhancing the biological CO_2 uptake capacity by forests and soils.

Carbon dioxide capture and storage. Preventing CO_2 releases from fossil fuel burning to the atmosphere.

This paper focuses on the last climate change mitigation option, analyses the rationale, advantages and disadvantages of CO_2 capture and storage (CCS) as a measure to for sizable and lasting reductions of CO_2 releases to the atmosphere with a particular view on its potential implications for energy security.

Carbon dioxide capture and storage

CCS is the separation of carbon dioxide from carbon containing fuels either before, during or after the conversion process to the desired energy product with subsequent transport of the separated CO_2 to a storage location where it can be safely isolated from the atmosphere over long time periods. If techno-economically viable and publicly acceptable, CCS could be a greenhouse gas mitigation (GHG) option that would allow the continue use of fossil fuels even in a drastically GHG emission constrained future. Moreover, the application of CCS to biomass energy conversion could result in the net removal of CO_2 from the atmosphere (often referred to as "negative emissions") by capturing and storing the atmospheric CO2 taken up by the biomass.

The techno-economic feasibility of CCS depends on several factors: the size and number of emission sources and their distances from suitable disposal sites. In the power generation and industrial sectors the sources, typically have large emission volumes that make them amenable to CO_2 capture. The other sectors are characterized by a large number of point source emissions but these tend to be small, and in the case of the transportation sector mobile, which makes them less amenable to capture.

However, except for some pilot projects, CCS is a commercially unproven technology and surrounded by a number of uncertainties ranging from its cost-effectiveness, potential applicability and capacity to declining efficiencies, thus higher demand for primary resources, safety and security of storage as well as social acceptability. The following section will address each of these issues.

Capture

Capture is the process of separating CO_2 from energy conversion processes and producing a concentrated stream of CO_2 at high pressure that can readily be transported to a storage site. For reasons of practicality and economics, the applicability of capture is largely limited to large point sources of CO_2 such as large fossil-fueled and biomass power plants, heating plants, refineries, energy-intensive industrial processes and synthetic fuel or hydrogen production facilities. Likewise, a high degree of purity reduces transport costs and storage requirements. Today, CO_2 separation is practiced in the chemical industry usually with the objective to purify other gas streams (e.g., ammonia, hydrogen production and natural gas treatment) with the CO_2 usually released to the atmosphere. However, capture at large commercial fossil power plants has not yet been practiced.

There are four basic approaches to CO_2 capture: Pre-combustion, oxyfuel combustion and post-combustion capture (see Figure 1):

Pre-combustion: Fossil fuels or biomass retort in a reactor with steam and oxygen (air or pure O_2) to produce synthesis gas - essentially hydrogen (H_2) and carbon monoxide (CO). A subsequent shift reaction of the CO with steam generates additional H_2 and CO_2. Separating the resulting mixture of H2 and CO_2 leads to two relatively pure product streams. The hydrogen stream then may fuel electricity and heat generation, in future power vehicles and fuel other energy processes or serve as a chemical feedstock. The CO_2 stream has attractive features, i.e., is relatively concentrated and often of high pressure. If the CO_2 is not released to the atmosphere, hydrogen is a carbon-free fuel.

Steam methane reforming (SMR) is a mature and commercially proven hydrogen production process. Regarding coal, pre-combustion would be deployed at power plants using integrated gasification combined cycle (IGCC) technology.

Oxyfuel combustion: Oxygen (95 plus percent purity) instead of air is used in the combustion process. In the virtual absence of nitrogen the combustion products consists mainly of water vapour and CO_2. The resulting flue gas has high CO_2 concentrations but at relatively low pressures. After removal of the water vapour by condensation and other combustion products

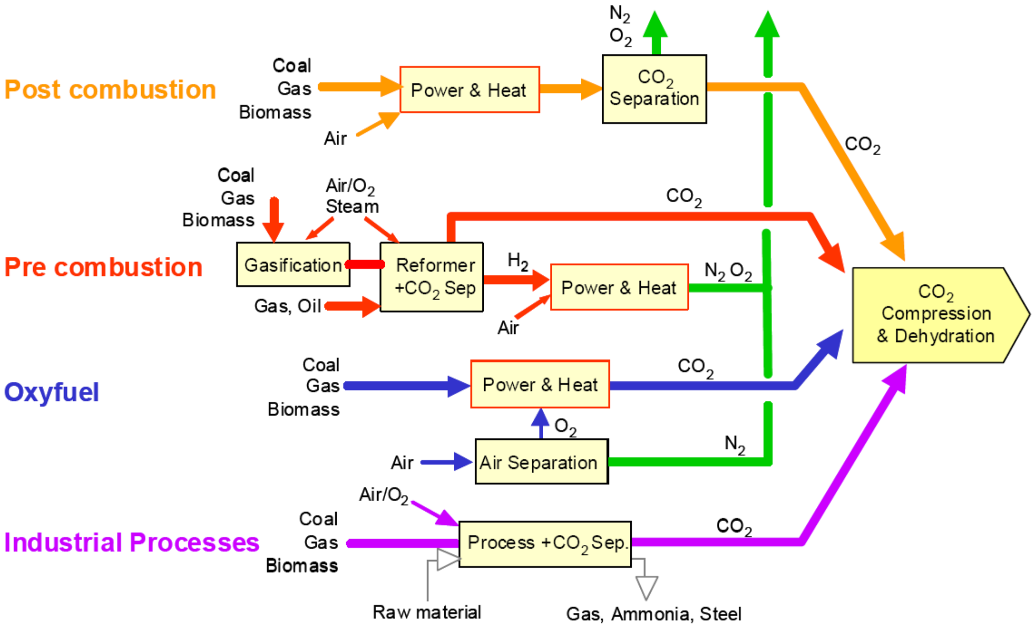

Figure 1: Overview of CO2 capture processes and systems (Source: IPCC, 2005)

(incomplete combustion, sulfur dioxide, nitrogen compounds, etc), the resulting CO_2 stream needs pressurization. Oxyfuel combustion is currently in a demonstration phase.

Post-combustion: CO_2 is separated from the flue gases produced by the combustion process using air using a liquid solvent (e.g., monoethanolamine – MEA). Because nitrogen is the main constituent of a combustion process using air, the concentration of CO_2 in the flue gas stream is relatively small (typically 3–15% by volume) and of low pressure. Post-combustion capture, therefore, is an inherently energy-intensive process.

Industrial processes: In many large industrial processes, e.g., natural gas treatment and ammonia production, separating CO_2 is already common place to purify other industrial gas streams. CO2 separation could be extended to include other industrial process including the production of certain petrochemicals, iron and steel and cement.

The effectiveness of CO_2 capture systems is largely a function of technology complexity and economic reasoning. Because CO_2 capture systems require additional equipment and energy input, they not only incur additional costs but also a significant energy penalty. The latter adversely affects overall conversion efficiencies, increases the fuel input per net kWh produced and adds to the CO_2 emissions to be captured as well as to most other pollutants and wastes. Costs and energy penalty depend on the degree of CO_2 capture. Though technically possible it is neither practical nor economical to capture 100 percent of the carbon emissions even from a large point source. As well, the amount of CO_2 captured is not equal to the amount of CO_2 emission avoided (see Figure 2). For an overall capture factor of 90 percent, the energy penalty is up to 40 percent for modern coal plants, up to 25 percent for IGCC plants and natural gas combined cycle (NGCC) plants compared with similar plants without CCS.

Transport

The captured CO_2 is transported to the storage site in pipelines or tanks. Pipeline transport of gases and liquids including of CO_2 are mature and well understood. Pipeline is the preferred mode for long-distance transport of liquids and gases. CO_2 pipelines already extend over thousands of kilometers transporting CO_2 for enhanced oil recovery and other purposes.

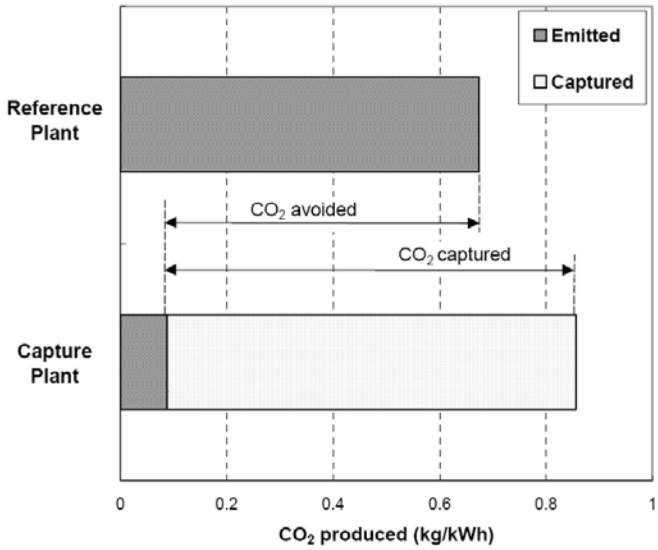

Figure 2: Difference between CO_2 captured and CO_2 emissions avoided (Source: IPCC, 2005).

Needless to say the transported substance should be essentially free of corrosive substances and meet "pipeline quality" standards. For reasons of practicality and economics, the captured CO_2 is pressurized to its fluid state (greater than 8 MPa at ambient temperature) which makes it denser and easier to transport and the reason for the preference of capture technologies that generate a high pressure CO_2 stream.

Similar to liquefied natural gas (LNG) or liquefied petroleum gases (LPG), CO_2 also can be transported as a liquid at a temperature well below ambient in ships, trucks or rail cars using insulated tanks. The properties of liquefied CO_2 are similar to those of LPG. LPG trade by marine tankers and distribution by rail and trucks are mature technologies and common place all over the globe.

Uncertainty and risks of CO_2 transport are generally lower that those of natural gas transport, in part due to the inflammability of CO_2. Leakages from pipeline operation are low and largely the result of pipe venting for maintenance and repairs. Pipeline rupture could cause local high CO_2 concentrations which could cause harm to people and animals. Boil-off leakage from cryogenic CO_2 transportation is about 2 percent per 1,000 km which could be further reduced through capture and re-liquefaction.

Storage

Two major options for CO_2 storage are under consideration, i.e., in geological formations below the earth's surface and the deep ocean. In each case, the purpose is the long-term (at least several centuries) isolation of the injected and stored CO_2 from the atmosphere.

Geological formations: Large underground natural reservoirs have trapped CO_2 for millions of years in the Earth's crust. This suggests the possibility of storing anthropogenic CO_2 in suitable geological formations as long as the reservoirs integrity is not compromised. Geological storage of CO_2 includes depleted oil and gas fields, deep saline aquifers and unminable coal beds. Geological storage involves the pressurized injection of CO_2 into porous rock formations (sedimentary basins) that previously held or still hold viscous fluids such as oil, natural gas, water, brines or even CO_2. Suitable reservoirs feature highly impermeable cap rocks, absence of potential leakages pathways and effective seal and trapping mechanisms. The most effective storage sites are those where CO_2 is trapped permanently under a thick, low permeability seal, or when the CO_2 is converted to solid minerals or adsorbed on the surfaces of coal micro-pores.

Injecting CO_2 in mature oil fields may mobilize additional oil and gas and enhance overall reservoir output. Standard production technologies usually extract only up to 40 percent of the oil in place. Two factors contribute to the enhanced oil recovery (EOR) effect: Re-pressurization of the reservoir via the pressurized CO_2 injection and miscible displacement. Under suitable reservoir pressure and oil density conditions, the injected CO_2 mill mix thoroughly with the oil in place and reduce its viscosity and density allowing additional oil production. Recycling of the CO_2 after the oil has been produced and, after filed closure, sealing off all injection and production wells then makes the oil field a permanent CO_2 storage site.

The recovery of coal bed methane (CBM), i.e., methane found in coal seams, is another area where CO_2 storage may generate energy benefits. The storage requirement restricts CBM to unminable coal occurrences.

The global technical (i.e., not necessarily economical) storage potential in geological formations is estimated at 7,000 to 11,500 $GtCO_2$ (IPCC, 2005). Deep saline aquifers hold the largest storage potential (6,000 - 10,000 $GtCO_2$) followed by d depleted oil and gas fields (900 - 1,300 $GtCO_2$) and unminable coal seams (60 – 150 $GtCO_2$).

The uncertainties associated with CO2 storage in geological formations and retention/leakage are minor given the long and effective trapping effect of natural CO_2, natural gas and oil reservoirs. Still, incompletely sealed production and injection wells, undetected faults and fractures cracks eventually provide for leakage to the atmosphere. A retention factor higher than 99 percent over 1,000 years can be expected. Major releases could occur if the integrity of reservoirs is affected by anthropogenic acts or seismic activity. Potential impacts from leakages are elevated CO_2 concentrations in the shallow subsurface that could affect plants and subsoil animals, and contamination of groundwater aquifers. High above surface CO_2 concentrations in the air could harm animals or people.

Ocean storage utilizes the solubility of the acidic gas CO_2 in water and the natural function of oceans as CO_2 sinks. CO_2 exchanges between the atmosphere and the oceans occur when their concentrations are out of equilibrium. An increase in atmospheric CO_2 concentrations leads to gradual removal by the oceans until equilibrium is reached again (a process measured in centuries but which is reversible). Currently, ocean uptake triggered by the anthropogenic CO_2 emissions that led to higher atmospheric concentrations is about 7 $GtCO_2$ per year. It is expected that over the next several centuries the oceans will continue to take up most of the anthropogenic CO2 released to the atmosphere by the ocean surface seawater and subsequently mixed with deep ocean waters.

Because of the slow interaction between the upper and lower layers of the oceans, most of the anthropogenic CO_2 still resides within the first 1,000 me of the oceans. Deep ocean disposal makes use of this slow interaction between various layers and the deeper CO_2 is injected the longer the retention time. At depths above 500 meters CO_2 remains in a gaseous state and injection has to occur as diffused as possible to avoid the gas reaching the ocean surface before fully dissolved. Below 500 meters the pressure regime is too large for it to exist in a gaseous state and CO_2 becomes a liquid. Still CO_2 is less dense than water and injected CO_2 tends to rise to the surface. The low temperature regime in oceans at that depth, however, would cause the formation of CO_2 hydrates at the droplet wall. The high pressure then compresses the droplet and accelerates its dissolution in water before the droplet rises significantly.

Below 3,000 meters CO_2 is sufficiently compressed and thus is denser than seawater. If injected via a fix pipeline or seafloor platform, it is likely to form a "CO_2 lake". This lake would dissolve slowly either by the larger droplets descending to the seafloor or smaller droplets dissolving in the surrounding seawater.

Oceans cover over 70% of the Earth's surface with an average depth of 3,800 m and already contain enormous amounts of CO_2 – about 50 times the amount that currently resides in the atmosphere. There appears to be no physical limit on the amount that could be stored in the oceans. A limiting factor may arise from local changes in the pH value of seawater caused by the injected acid CO_2 and the overall rate of dispersions over the entire ocean. High volume injection and pools of liquid CO_2 at the ocean floor could change the local chemistry and adversely affect ocean flora and fauna. Another limiting factor is the equilibrium between the CO_2 stored in the ocean and the concentration in the atmosphere. It is estimated that the deep injected CO_2 will remain in the oceans for at least several hundreds of years with the bulk of it staying indefinitely. Depending on the depth of injection, the fraction retained after 100 years is 65-100 percent and 30-85 percent after 1,000 years (the lower number is for injection at 1,000 m depth, the higher number at 3,000 m).

Ocean storage has not yet been deployed or thoroughly tested and thus carries large uncertainties and risks ranging from retention time to the potential environmental impacts. Ongoing experiments, field testing and model simulation will eventually determine the practicality, costs and benefits of ocean storage of CO_2.

Energy Security of CCS

Energy security is an integral part of national security with the objective to preserve territorial autonomy. More specifically, energy security aims at the minimization of economic and other risks associated with a nation's or region's energy supply. It has been variably defined to imply:

- "Energy security" is the ability of a nation to muster the energy resources needed to ensure its welfare (Victor, 2005).
- The continuous availability of energy in varied forms, in sufficient quantities, and at reasonable prices (Goldemberg, 2000).
- Security of energy supply, competitiveness and protection of the environment (EP, 2001).
- A reliable, affordable, and environmentally sound energy system (USNEPDG, 2001).

Energy security may be exposed to external and internal uncertainties. External uncertainty includes supply interruptions due to geopolitical tension between supplier and recipient country, natural disasters, sabotage, market shifts and international price fluctuations. Internal uncertainty derives from inadequate transport or transmission logistics, cost and financial limitations as well as poor planning and preparedness, weak maintenance and management as well as deficient governance.

The traditional approach to energy security has been to build up strategic fuel stocks and to diversify energy supplies, both internally and externally. Internally, by way of maximizing the use of domestic resources, preferably based on domestic technologies; externally, by way of selecting a variety of products from a diversity of supplies from different geographical regions. However, there is no universal recipe to or consensus on the level of energy import dependence considered acceptable or sustainable, and this varies from country to country.

Although predominantly viewed as a supply issue, an important measure to enhance energy security may well be using less energy to accomplish the same tasks or supply the same energy services, in short using energy more effectively and efficiently. The European Commission in its Green Paper on energy security stated, "only a policy that is also geared to control demand can lay the foundation for sound energy supply security policy" (EC, 2000). In addition, security encompasses the notions of vulnerability and reliability, i.e., to derive more energy services from options that are inherently less vulnerable, being more diverse, dispersed or renewable.

Energy security also encompasses different time-scales ranging from the immediate – a power station break-down today causing a nation-wide black-out – to the very long-term – the risk that world oil production peaks within next 10 years (pessimistic and narrow scenario of oil occurrences; Campbell, 2003) or 40 years (optimistic and broader oil occurrence scenario; Wood *et al.*, 2004) and extreme oil market price volatility. Then there is the risk of climate change, which may force the premature retirement of previous investments.

A low carbon economy could also have long-term security benefits compared with the current fossil fuel dependent system. It would be associated with a combination of high-energy efficiency end-use technologies (thus using less MJ per unit of service), the use of resources that are either renewable (and often local) or plentiful and nuclear power.

But a low carbon economy is no complete insurance against all risks. While energy efficiency, renewable energy and nuclear power hedge against fossil fuel dependence, they are no effective response to a sudden supply crisis. For one, these options are usually fully utilized and leave little margin for additional output. For another, their incremental expansion is a time-consuming process requiring many years until new capacities become operational. Transmission networks, pipelines, distribution systems, et cetera, continue to present risks for failure and disruption irrespective of a low-carbon economy. Therefore, it is necessary to consider possible policy responses to a wide range of security issues. One of the issues is the potential role of CCS and energy security.

Energy Security and CCS

Does carbon capture and storage contribute to or reduce energy supply security? As so often there is no straightforward answer other than: it depends. It depends on a country's resource endowment and technology infrastructure, its size and ability to influence international energy markets and its geographical location.

At a first glace, one is tempted to conclude that CCS would adversely affect supply security simply because of the energy penalty associated with the capture, transport and storage of CO_2. The energy penalty increases the use of primary resources required for the provision of a given unit of energy service. If the fuel is imported, CCS translates into higher energy import dependence, and if the fuel is a domestic resource, resources are depleted at a faster rate. Higher energy import dependence or faster domestic resource depletion inherently burden national energy security. In addition there are also cost penalties such as higher energy import bills and overall higher energy costs to the economy. So far the costs of CCS have only been addressed in superficial generic fashion. Because CCS is meant to help mitigate climate change, the added costs of CCS must be assessed in the context of the entire range of mitigation options and the costs of adaptation. A brief comparison of the cost ranges of avoided CO_2 emissions follows below. Still CCS costs are real and (everything else being equal which of course never is) inherently make energy services more expensive and, to the extent the higher costs are passed on to the final consumer reduce affordability and energy security.

CCS, however, is a more complex than merely higher import dependence and import bills. The recent tightness of the international oil market is to a large extent the result of the oil demand developments in China and India. Right now the oil market's ability to absorb any supply shock is minimal and barring a major global economic recession oil demand is set to rise. So will prices until additional supplies come online, alternatives to oil products penetrate the market place or oil becomes unaffordable (with all the economic consequences). Sure, investment in exploration of conventional oil will eventually bring on additional supplies but increments will be small in comparison with growth in demand. Investment in the production and upgrading of unconventional oil such as tar sands, extra heavy oils or shale oil require long lead times before making an inroad in the international oil market. Moreover, the production of marketable products from unconventional oils by itself is an energy and carbon-intensive process. While unconventional oil in the presence of US$60 plus per barrel represents security benefits, the added carbon emissions counteract the objectives of climate protection and thus threaten overall security.

Australia, China, India, Russian Federation, South Africa or the United States are endowed with substantial coal reserves and resources. Here CCS could make a positive impact on energy security as well as mitigate CO_2 emissions. Interest in synthetic liquid fuels as a measure to improve oil supply security surfaces regularly whenever oil prices spun out of control. Coal-based synthetic fuel production with CO_2 capture could generate relatively pure CO_2 streams, especially if based on polygeneration, e.g. plants that produce synthetic liquid or gaseous fuels plus electricity (Williams et al, 2000; Celik et al., 2005). Studies have shown that on an equal energy basis CO_2 emissions along the full fuel-cycle form coal-based dimethyl ether (DME) production with CCS could be up to 75 percent lower than those from diesel derived from crude oil (Celik et al., 2005). Hydrogen fuel production from domestic natural gas or coal using an external non-carbon heat source, i.e., nuclear process heat, plus CCS could reduce CO_2 releases to the atmosphere to very low levels (Miller & Duffey 2005).

Low or CO_2-free hydrogen production from renewables or nuclear power combined with carbon captured from fossil energy conversion processes could also be combined to generate methanol. Here the captured CO_2 would be recycled and used, say, as a transportation fuel. This would eke out oil and gas resources, provide additional time for the commercialization of non-carbon alternatives and reduce overall emissions. However, the captured CO_2 will eventually end up in the atmosphere because carbon capture from millions of tail pipes is unpractical. In contrast, if the CO_2 captured originates from biomass conversion, this would genuinely be a lowest or zero CO_2 emission option. Methanol production from captured CO_2 and hydrogen makes sense only in the absence of a hydrogen infrastructure. Otherwise this concept lacks economic and environmental rationale, i.e., why would one contemplate the contamination of clean hydrogen with CO_2?

In any case, on certain conditions CCS has the potential to improve energy security. CCS could contribute to the diversification of technologies and fuels, especially when substituting domestic coal for energy services based on oil or gas imports. In industrial processes where CO_2 is separated for other purposes, CCS has no security implications but tangible climate change benefits. The CCS benefits for mitigating climate change and energy security, however, can not be generalized and must be assessed on a case-by-case basis.

Biomass conversion from sustainably grown feed stocks to bio-fuels, electricity or heat with CCS could be characterized as negative CO_2 emissions. For example, bio-ethanol produced from sugar cane generates a high concentration stream of CO_2 at atmospheric pressure during the fermentation process that can be captured and subsequently stored. Bio-ethanol is a direct total or partial replacement for oil products in the transportation sector. Because dedicated biomass production, including sugar cane, short-rotation woody crops such as hardwood trees, herbaceous crops and vegetable oils are locally grown, CCS in this case would represent a win-win situation: (a) improved energy security through reduced import dependence, protection against international energy market price volatility and reduced stress on domestic fossil resources and (b) climate protection. In addition, biomass and CCS could generate sizable local economic benefits.

Other aspects of energy security related to CCS such as technology and system reliability, natural disasters, rapid market shifts or potential exposure to sabotage and terrorism are no different from energy supply pathways without CCS.

Economic Considerations

The concept of carbon dioxide capture and storage is entirely driven by climate change considerations. The investment and operating costs of carbon capture (separation plus compression), transport, and storage (including measurement, monitoring and verification) are real and add to the overall costs of supplying a particular energy service. CCS, therefore must be assessed in comparison with the full menu of other mitigation options from efficiency improvements throughout the energy system, fuel switching to less carbon intensive fuels, increased use of nuclear power and renewable energy sources to biological sinks, and reduction of non-CO_2 greenhouse gas emissions as well as adaptation to climate change.

The most recent cost assessment of CCS based on fossil-fueled electricity generation vary widely between US$0.01 to US$0.05 per kWh depending on fuel, fuel costs and generating technology (pulverized coal power plant, natural gas combined cycle or integrated gasification combined cycle), the capture system, transport mode and transport distance of the captured CO_2 as well as the specific conditions of the storage site. Retro-fitting of existing plants tends to be more costly than integrating carbon dioxide capture into new plants. However, one little or no experience exists with the intricacies of a full CCS system and uncertainties regarding the overall techno-economic performance are non-trivial. But there is also room for economies of scale and technology learning which could reduce the costs of CCS as experience in the use of CCS accumulates.

If captured CO_2 is used for enhanced oil recovery or other industrial processes, CO_2 sales revenues or by-product credits would accrue and reduce overall costs of CCS.

In terms of CO_2 emissions avoided the added costs of CCS translate into US$20 to US$220 per tonne of CO_2. Many other mitigation options fall in this cost of avoided CO_2 range and the actual economic performance of CCS has to be determined on a case-by-case basis.

Concluding Remarks

Carbon dioxide capture and storage expands the menu of options for mitigating climate change which increases overall flexibility in achieving effective greenhouse gas emission reductions. The actual deployment of CCS will depend on the technology performance of future carbon dioxide capture to storage pathways, costs, environmental aspects and public acceptance. Some technologies along the pathway have already reached a high degree of maturity; several exist at a different scale than would be required in a viable CCS context, while others are in an embryonic state and there is hardly any experience available in the configuration of large-scale and fully integrated CCS systems. In a GHG emission constrained world, CCS has to compete against other GHG mitigation options and adaptation. Except for ocean storage with limited knowledge of the potential impacts of large scaleCO_2 injection, the environmental risks of CCS (retention time, leakage, sudden releases) appear manageable and comparable to the operating risks of the handling of oil or natural gas regarding leakage, transport and storage.

Based on economic and environmental considerations, CCS may first be deployed as a cost-effective GHG mitigation option where capture from large point sources occurs in the vicinity of depleted oil and gas fields.

The implications of CCS for energy security depend on variety of factors and no straightforward causality exists. One the one hand, if applied to combustion processes that rely heavily on imported fossil fuels, CCS could adversely affect energy security. The energy penalty of CCS not only increases import volumes - thus import dependence and geostrategic risks – but also an economy's exposure to international market price volatility. The additional technological complexity of a CCS system augments the total risk of technology component failure or malfunctioning.

On the other hand, if CCS stimulates energy import substitution through an intensified use of domestic fossil fuels, e.g., synthetic liquid fuel production utilizing a large coal resource base, it could enhance energy security. Depending of overall international energy market prices, CCS may increase but also decrease overall costs (at oil prices in excess of US$60 per barrel of oil synthetic liquid fuel production including CCS may well have economic benefits compared with imported oil). Under such conditions, CCS would improve energy security.

In any case, CCS inflate the overall costs of supplying energy services which inherently improves the comparative advantage of other CO_2 abatement options. Efficiency improvements throughout the energy system, renewables and advanced technologies including nuclear power will limit the deployment potential of CCS based on the costs of tonnes of CO_2 avoided as well as other environmental and regulatory considerations and public acceptance.

Finally, energy security carries a price tag comparable to an insurance premium. Energy supply options that lower insurance premiums and simultaneously fulfill environmental and sustainable development objectives, enhance overall socio-economic welfare and national security.

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