Concept Note

Power plant CO_2 capture technologies

Risks and risk governance deficits

international risk governance council

Abbreviations used in the text:

CCS	Carbon Capture and Storage (or Sequestration)
CO_2	Carbon Dioxide
CSLF	Carbon Sequestration Leadership Forum
EPRI	Electric Power Research Institute
EU	European Union
EU ETS	European Union Greenhouse Gas Emission Trading System
GHG	Greenhouse gas
IEA	International Energy Agency
IGCC	Integrated Gasification Combined Cycle
IPCC	Intergovernmental Panel on Climate Change
MEA	Monoethanolamine
MHI	Mitsubishi Heavy Industries
NGCC	Natural Gas Combined Cycle
PC	Pulverised coal
SO_2	Sulphur Dioxide
Syngas	Synthesis gas (or synthetic natural gas)
UK	United Kingdom
US	United States
USDOE	US Department of Energy
USEPA	US Environmental Protection Agency

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Preface

IRGC is an independent organisation whose purpose is to help the understanding and management of emerging global risks that have impacts on human health and safety, the environment, the economy and society at large. IRGC's work includes developing concepts of risk governance, anticipating major risk issues and providing risk governance policy recommendations for key decision-makers.

Every IRGC project commences with the writing of a "concept note" to describe the particular risk issue being addressed. IRGC has already completed a project on the wider risk governance issues posed by Carbon Capture and Storage (CCS), and published its policy recommendations in the policy brief "Regulation of Carbon Capture and Storage" in early 2008[1]. The objective of this concept note is to draw the attention of policymakers and business decision-makers to the particular risks associated with one particular element of the CCS value chain, that of carbon capture technologies.

The document is not intended to be a complete and in-depth description of the technologies available for power plant CO_2 capture and the risk governance issues raised by them but, rather, provides a brief summary of the most relevant and urgent issues. It also offers a preliminary identification of risk governance deficits and some initial recommendations for how they may be addressed.

More information on this document can be obtained from Malin Samuelsson, at malin.samuelsson@irgc.org

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[1] IRGC's policy brief "Regulation of Carbon Capture and Storage" was published in early 2008 and can be downloaded from www.irgc.org

Contents

Introduction

The threat of global climate change induced by human activities has spurred growing international interest in technology to capture and sequester the carbon dioxide (CO_2) emitted from electric power plants – a major source of the greenhouse gas (GHG) emissions driving climate change. As an emissions abatement measure, carbon capture and storage (or sequestration) – widely known as CCS – has to date received less attention than other options such as increasing the use of non-fossil energy sources (renewables and nuclear) and improving the efficiency of energy use (in buildings, factories and transport systems) so as to reduce the demand for energy. Indeed, until recently the term carbon sequestration generally meant the uptake of atmospheric CO_2 by trees and other forms of biomass. Today the term also includes the capture and storage of CO_2 produced by large industrial sources.

Because of its growing importance in climate policy deliberations, the risks and governance issues of CCS are receiving increased attention. Concerns about CCS have focussed mainly on issues related to storage, especially geological storage, the dominant method proposed for disposing of captured CO_2. In contrast, the purpose of the present note is to highlight and discuss risk governance issues related to the first stage of the CCS process, namely the capture of CO_2.

Although capture systems can be applied to a variety of industrial processes, the focus of this report is on fossil-fuelled power plants. These plants are responsible for an estimated 40% of the world's fossil fuel-derived carbon emissions [IPCC, 2007a]. While most of these emissions arise from burning coal, power plants fired by natural gas are also of concern[2]. Thus, the potential for CCS to reduce these emissions by up to 90% with current technology [ZEP, 2009] makes the deployment of CCS an important option in efforts to reduce GHG emissions.

The following sections of this concept note give, first, a brief overview of CCS and the reasons for its growing importance. Then, the technological options for CO_2 capture at electric power plants are discussed. That sets the stage for a closer examination of the major risk governance deficits that must be considered as deployment of CO_2 capture systems moves forward.

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[2] Emissions from petroleum combustion also may be of concern in some locations. Globally, however, this is a minor source of CO_2 emissions from the electric power sector.

1. Why the interest in CCS?

On first hearing of it, the idea of CCS may sound a bit far-fetched. To avoid emitting billions of tons of CO_2 to the atmosphere, engineers propose to equip coal- or gas-burning power stations with chemical plants that strip CO_2 from the flue gases before they go up the chimney. The concentrated CO_2 would then be compressed to a liquid and injected deep underground where it would be trapped by impermeable layers of rock. Gradually, over centuries, it would transform into solid carbonate minerals. Sequestering CO_2 in this way would not be cheap – if applied to an existing power plant today, the cost of generating electricity would nearly double. Surely, one would think, there must be an easier way to reduce CO_2 emissions from power plants.

Such was the general view when the idea of CCS was first proposed as a GHG mitigation strategy over three decades ago. But in recent years things have changed. Scientists, engineers and policy analysts have taken a closer look at CCS and found that it could indeed be an important player in mitigating global climate change.

Worldwide interest in CCS stems principally from three factors. First, there is growing recognition that large reductions in global CO_2 emissions are needed to avoid serious climate change impacts – as much as an 85% reduction in emission by the middle of this century, according to the Intergovernmental Panel on Climate Change (IPCC) [IPCC, 2007a]. Because electric power plants are a major contributor to GHG emissions, large reductions cannot be achieved unless their emissions also are greatly curtailed.

Second, there is the realisation that such large emission reductions cannot be achieved easily or quickly simply by using less electricity or replacing fossil fuels with alternative energy sources that emit no CO_2. The reality today is that the world relies on fossil fuels for over 85% of its energy use. Changing that picture dramatically will take time. CCS thus offers a way to get large reductions in CO_2 emissions from the power generation sector (as well as from part of the industrial sector) before cleaner, more sustainable technologies can be widely deployed.

Finally, energy-economic models show that adding CCS to the suite of other GHG reduction measures significantly lowers the cost of mitigating climate change when deep reductions in emissions are required [Edmonds, 2008]. The IPCC also affirmed CCS to be a major component of a cost-effective portfolio of technologies to mitigate climate change [IPCC, 2007a].

2. The role of CO_2 capture

CO_2 capture is the first critical step of the CCS process – and also the most expensive. A variety of commercial technologies for separating (capturing) CO_2 are widely used in industrial processes today, typically as a purification step [Rubin, 2008]. Common applications include the removal of CO_2 impurities in natural gas treatment and the production of hydrogen, ammonia and other industrial chemicals. In most cases, the captured CO_2 stream is simply vented to the atmosphere. In a few cases it is used in the manufacture of other chemicals [IPCC, 2005].

CO_2 has also been captured from a portion of the flue gases produced at power plants burning coal or natural gas. Here, the captured CO_2 is sold as a commodity to nearby industries such as food processing plants. Globally, however, only a small amount of CO_2 is utilised to manufacture industrial products, and nearly all of it is soon emitted to the atmosphere (think about the fizzy drinks you buy).

As a climate change mitigation strategy, CCS is best suited for facilities with large CO_2 emissions. Power plants are the principal target because they account for roughly 80% of global CO_2 emissions from large industrial facilities – mostly from burning coal. To date, however, there has been no application of CO_2 capture at the scale of a commercial power plant (e.g., hundreds of megawatts), although designs of such systems have been widely studied and proposed. In some cases, small pilot-scale projects have been launched as a first step toward a commercial-scale facility[3].

Since most anthropogenic CO_2 is a by-product of the combustion of fossil fuels, CO_2 capture technologies are commonly classified as either pre-combustion or post-combustion systems, depending on whether carbon is removed before or after a fuel is burned. A third approach, called oxyfuel or oxy-combustion, does not require a CO_2 capture device. This concept (described below) is still under development and not yet commercial.

In all cases, the aim of CO_2 capture is to produce a pure CO_2 stream that can be permanently sequestered and stored, typically in a geological formation[4]. This requires high pressures to inject CO_2 deep underground. Thus, captured CO_2 is first compressed to a dense "supercritical" state, where it behaves as a liquid, making it easier and much less costly to transport and store. The CO_2 compression step is commonly included as part of the capture system since it is usually located at the industrial plant.

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[3] One recent example is the Mountaineer power plant, West Virginia, US, where a 20-megawatt CCS validation project using an ammonia-based capture process started in September 2009, with a view to scale-up to a commercial-size application in 2015 [AEP, 2009].

[4] Other storage options, including mineralisation, utilisation and injection into deep ocean waters have also been studied and found to be not commercially viable at this time. For a detailed discussion of alternative storage options see [IPCC, 2005].

3. Capture options for power plants

Here we briefly describe each of the three major approaches to CO_2 capture to provide context for the discussion of risks and risk governance issues that follow. More detailed descriptions of CO_2 capture technologies can be found in the technical literature (e.g., [IPCC, 2005; Science, 2009]) and at a variety of CCS-related websites (e.g., [IEAGHG, 2009]).

3.1 Post-combustion capture

As the name implies, these systems capture CO_2 from the flue gases produced when fossil fuels or other carbonaceous materials (such as biomass) are burned in air. Combustion-based power plants provide most of the world's electricity today. In a modern coal-fired power plant, pulverised coal (PC) is burned in a furnace or boiler. The heat released by combustion generates steam, which drives a turbine-generator (Figure 1). Hot combustion gases exiting the boiler consist mainly of nitrogen (from air) and smaller concentrations of water vapour and CO_2. Additional constituents, formed from impurities in coal, include sulphur dioxide (SO_2), nitrogen oxides and particulate matter (fly ash). These are pollutants that must be removed to meet environmental standards. Subsequently, CO_2 can be removed.

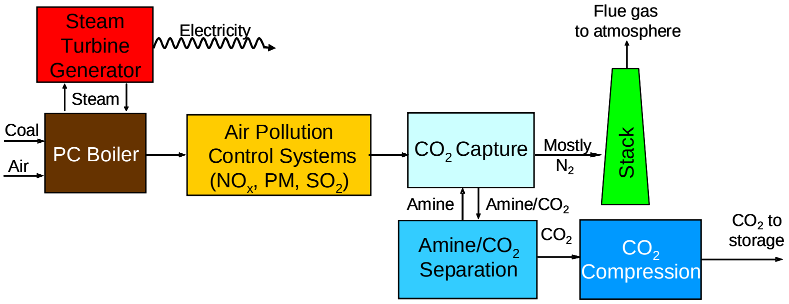

Figure 1. *Schematic of a coal–fired power plant with post-combustion* CO_2 *capture using an amine scrubber system. Other major air pollutants (nitrogen oxides, particulate matter and sulphur dioxide) are removed from the flue gas prior to* CO_2 *capture.*

The most effective method to remove CO_2 from the flue gas stream of a PC plant is by chemical reaction with a liquid solvent. The most common are a family of organic compounds known as amines, one of which is monoethanolamine (MEA). In a vessel called an absorber, the flue gas is "scrubbed" with an amine solution, typically capturing 85-90% of the CO_2. The CO_2-laden solvent is then pumped to a second vessel, called a regenerator, where heat is applied to release the CO_2. The resulting concentrated CO_2 gas stream is then compressed and piped to a storage site, while the depleted solvent is recycled back to the absorber. Figure 2 shows an amine system installed at a coal-fired power plant in the US.

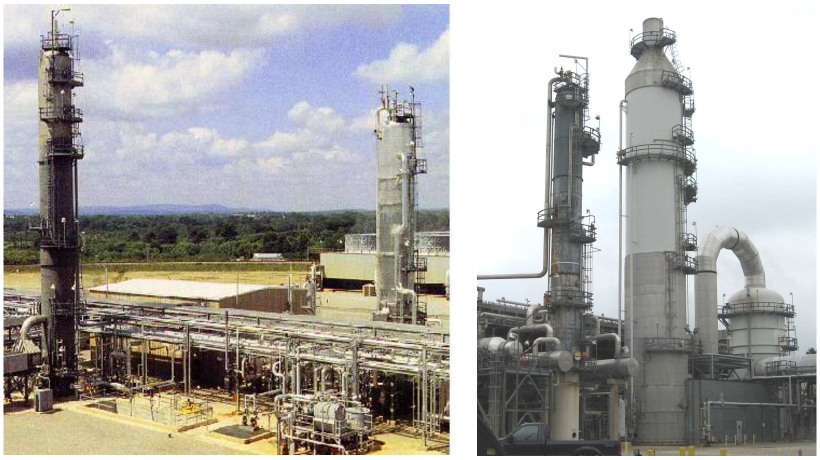

Figure 2. *Amine-based post-combustion CO_2 capture systems treating a portion of the flue gas (~40 MW equivalent) from a coal-fired power plant in Oklahoma, USA (left) and a natural gas combined combustion (NGCC) plant in Massachusetts, USA (right). The captured CO_2 is sold to nearby food processing plants. (Photos courtesy of ABB Lummus, Fluor Daniels and Chevron)*

The same post-combustion capture technology also can be applied to flue gases emanating from a natural gas-fired boiler, or a more efficient natural gas combined cycle (NGCC) power plant, depicted in Figure 3. Although the CO_2 concentration is more dilute than in coal plants, high removal efficiencies are still achieved with amine-based capture. The absence of impurities in natural gas facilitates the capture process since a clean flue gas stream is needed for effective CO_2 capture.

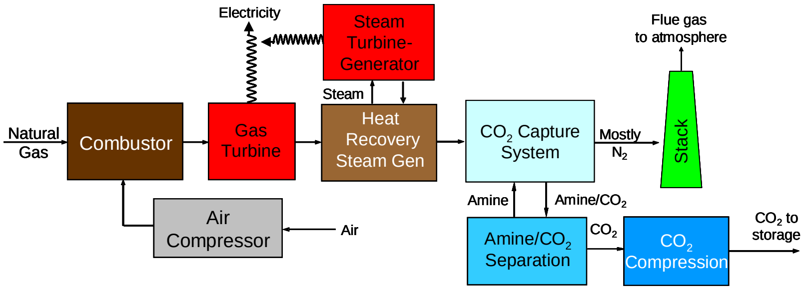

Figure 3. *Schematic of an amine-based post-combustion CO_2 capture system applied to a natural gas combined cycle (NGCC) power plant.*

3.2 Pre-combustion capture

To remove carbon from fuel prior to combustion it must first be converted to a form amenable to capture. For coal-fuelled plants, this is accomplished by reacting coal with steam and oxygen at high temperature and pressure, a process called partial oxidation, or gasification. The result is a gaseous fuel consisting mainly of carbon monoxide and hydrogen – a mixture known as synthesis gas, or syngas, which can be burned to generate electricity in a combined cycle power plant similar to the NGCC plant described above. This approach is known as integrated gasification combined cycle (IGCC) power generation. After sulphur compounds and other impurities are removed from the syngas, a "shift reactor" converts the carbon monoxide to CO_2 via a reaction with steam (H_2O). The result is mixture of CO_2 and hydrogen. Another chemical solvent then captures the CO_2, leaving a stream of nearly-pure hydrogen that is burned to generate electricity, as depicted in Figure 4.

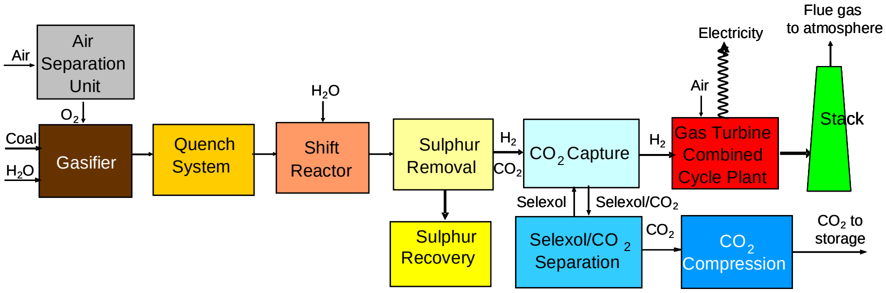

Figure 4. *Schematic of an integrated gasification combined cycle (IGCC) coal power plant with pre-combustion CO_2 capture using a water-gas shift reactor and a Selexol CO_2 separation system.*

Although the fuel-conversion steps of an IGCC plant are more elaborate and costly than traditional coal combustion plants, CO_2 separation is much easier and cheaper because of the high operating pressure and high CO_2 concentration of this design. Thus, the technology for pre-combustion capture is favoured in a variety of industrial processes, such as the manufacture of chemicals and fuels (Fig. 5).

Figure 5. *A pre-combustion CO_2 capture system used to produce synthetic natural gas (syngas) from coal at the Dakota Gasification Plant in North Dakota. About 3 Mt/y captured CO_2 is currently transported by pipeline to the Weyburn and Midale oil fields in Saskatchewan, Canada, where it is used for enhanced oil recovery (EOR) and sequestered in depleted oil reservoirs. (Photo courtesy of IPCC)*

Pre-combustion capture can also be applied to power plants using natural gas. As with coal, the raw gaseous fuel is first converted to syngas via reactions with oxygen and steam – a process called reforming. This is followed by a shift reactor and CO_2 separation, yielding streams of concentrated CO_2 (for storage) and hydrogen. This is the dominant method used today to manufacture hydrogen. If the hydrogen is burned to generate electricity, as in an IGCC plant, we have pre-combustion capture. While this capture method for gas is usually more costly than post-combustion capture, some power plants of this type have been proposed.

3.3 Oxy-combustion capture

Oxy-combustion (or oxyfuel) systems are being developed mainly as an option for conventional coal-fired power plants. Here, pure oxygen rather than air is used for combustion. This eliminates the large amount of nitrogen in the flue-gas stream. After the particulate matter (fly ash) is removed, the flue gas consists only of water vapour and CO_2, plus smaller amounts of pollutants such as SO_2 and nitrogen oxides (NO_x). The water vapour is easily removed by cooling and compressing the flue gas. Additional removal of air pollutants leaves a nearly pure CO_2 that can be sent directly to storage (see Figure 6).

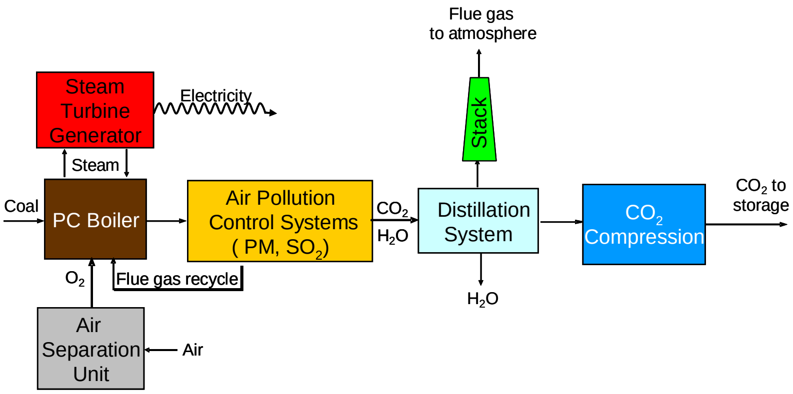

Figure 6. *Schematic of a coal-fired power plant using oxy-combustion. Approximately 70% of the CO_2-laden flue gas is recycled to the boiler to maintain normal operating temperatures. Depending on the purity of the oxygen from the air separation unit, small amounts of nitrogen and argon also enter the flue gas.*

The attraction of oxy-combustion is that it avoids the need for a costly post-combustion CO_2 capture system. However, it requires an air separation unit to generate the relatively pure (95-99%) oxygen needed for combustion. Roughly three times more oxygen is needed for oxyfuel systems than for IGCC plants, which adds significantly to the cost. Typically, additional flue gas processing is needed to reduce the concentration of conventional air pollutants to comply with environmental requirements and/or CO_2 purity specifications. Because combustion temperatures with oxygen are much higher than with air, oxy-combustion also requires much of the inert flue gas to be recycled back to the boiler to maintain normal operating temperatures. The system also must be carefully sealed to prevent leakage of air into the flue gas stream, as is common at most existing power plants.

As a CO_2 capture method, oxy-combustion has not yet been demonstrated at a commercial scale, but has been studied theoretically as well as in experimental test facilities. A major pilot plant project was launched in Germany in September 2008 (Figure 7). This plant is expected to provide the critical performance data needed to design a larger commercial-scale demonstration plant.

Figure 7. *An oxy-combustion pilot plant capturing CO_2 from the flue gas of a coal-fired boiler in Germany. The plant size is the electrical equivalent of approximately 10 MW. (Photo courtesy of Vattenfall)*

Although, in principle, oxyfuel systems can capture all of the CO_2 produced, the need for additional gas treatment systems decreases the capture efficiency to about 90% in most current designs. As with other capture technologies, higher removal efficiencies are possible but more costly. In general, engineers seek to optimise system designs to achieve the most cost-effective CO_2 removal.

In principle, oxy-combustion also can be applied to simple cycle and combined cycle power plants that employ gas turbines fuelled by combustion of natural gas or distillate oil. While such plants produce a relatively small share of total CO_2 emissions, they are especially important for providing peak power. In some cases they also provide baseload power. The use of oxy-combustion in gas turbine systems been studied analytically, with results showing a theoretical advantage over conventional plant designs in some cases [IPCC, 2005]. However, as a practical matter it would require significant and costly modifications to the design of current gas turbines and other plant equipment, with a very limited market potential. Thus, the current focus of oxy-combustion development is on coal-fired power plant applications.

4. Risk related to power plant CO_2 capture

A variety of risks are inevitably associated with the development and use of any technology, including those described above. The magnitude of a risk is commonly expressed as the product of two terms:

Risk = (Probability) × (Consequences)

Probability refers to the likelihood of some undesired outcome or event, such as the sudden failure of a CO_2 capture system or an inability to achieve the designed removal efficiency. The consequences of such an occurrence might be expressed in monetary terms or in other measures relevant to the event (such as a number of injuries or the duration of a loss of service). Thus, an event with a low probability of occurrence but high consequences should it occur could have a higher risk than a more likely event having small consequences.

In the context of power plant CO_2 capture systems, many risks are difficult to quantify reliably, mainly because at this point in time there is a lack of data on the probability of various events or outcomes at commercial facilities. Nonetheless, it is useful to consider the types of risks related to CO_2 capture systems, which are elaborated in the sections below.

4.1 Technical risks of capture systems

The first important question about CO_2 capture technology applied to power plants is: Will it work? Will it do the job of controlling CO_2 release to the atmosphere in a safe and reliable fashion, without compromising the reliability of electric power generation?

The answer today is that, based on substantial experience in other industrial settings and on limited experience in smaller-scale power plant applications, there is every expectation that current commercial capture systems will be safe and effective in large-scale power plant applications. However, until such systems are built and operated successfully at full scale in different settings there will remain uncertainty as to the technical risks of commercial power plant applications.

The technical risks of power plant CO_2 capture vary with the type of capture technology employed at different types of power plants. Each of the three general capture approaches described earlier has a unique set of concerns related to the capture system itself and its integration into the power plant. In addition there are technical risks associated with overall integration of the capture, transport and storage systems. These various risks are briefly described below.

Post-combustion capture

For post-combustion CO_2 capture at power plants, the major technical risk using current commercial amine systems is the tenfold scale-up in size required for full-scale operation. While a small number of amine capture systems have been operating reliably on flue gas slip streams equivalent to a power plant size of roughly 40 MW (see Figure 2), no power plant has yet employed CO_2 capture on the full flue gas stream. Experience with a variety of industrial processes shows that, when process equipment is scaled up by an order of magnitude, unexpected problems often arise. While such problems are usually remedied by changes in process design and/or operation, the initial installations of a new process typically have a greater risk of unacceptable performance and/or reliability. As a consequence, additional expenses and delays are incurred to correct the problem.

Such risks will remain until there is sufficient experience and understanding of large-scale capture system in power plant applications.

The power plant fuel type is another source of technical risk for post-combustion capture systems. In general, coal-fired plants pose greater risks than natural gas-fired plants because of higher contaminant levels in the flue gas stream, which can degrade the performance of the CO_2 capture system. Amine-based systems are especially sensitive to “acid gases”, particularly SO_2 generated by coal-fired plants. In recent years the design specifications for amine-based systems have required increasingly low levels of SO_2 in the inlet gas stream. This, in turn, requires desulphurisation of the flue gas beyond the prevailing regulatory requirements for SO_2 emissions.

At least three major vendors of amine-based systems, ABB Lummus, Flour-Daniels and Mitsubishi Heavy Industries (MHI), have experience with CO_2 capture installations on combustion-generated flue gas streams. To date only ABB Lummus has commercial installations on coal-fired power plants. MHI is conducting a series of tests of its process on coal-fired units prior to offering commercial guarantees.

Post-combustion capture using sorbents other than amines also are being developed and tested but are not yet commercial. Two types of ammonia-based systems are the leading alternatives proposed for coal-fired power plants. These systems promise to significantly reduce the energy requirements for CO_2 capture, and thus lower the cost. However, in terms of technical risk, these processes presently pose greater uncertainty than amine-based systems because of their earlier stage of development. Successful completion of pilot plant projects and subsequent scale-up to commercial-size plants are needed to fully assess their viability.

A variety of other advanced processes and concepts for post-combustion capture (e.g., solid sorbents, membranes) are at much earlier stages of research and development [NETL, 2009]. Such processes thus have much higher levels of technical risk for commercial applications at this time.

Pre-combustion capture

For pre-combustion CO_2 capture at IGCC power plants the dominant technical risk is again associated with scale-up from current industrial experience. Here, however, the primary concern is not the CO_2 capture process – water gas shift reactors and Selexol-based CO_2 separation units already operate at the scales needed for a commercial IGCC plant. Rather, the principal risk for electric utilities is the scale-up of the gas turbine power cycle. As noted earlier, decarbonisation of the syngas fuel stream leaves a hydrogen-rich fuel gas which is combusted to drive the gas turbine in a combined cycle power plant. To date, experience with hydrogen-fuelled gas turbines is limited to smaller-scale operations, mainly in the petroleum and petrochemical industries. Although gas turbine manufacturers are confident that larger machines, modified for hydrogen use, will operate safely and reliably in power plants, such capability remains to be demonstrated. So too does the transfer of commercial pre-combustion CO_2 capture technology to the power generation industry. Until full-scale IGCC plants with CO_2 capture are successfully demonstrated there will be technical risks (real and perceived) associated with that technology.

Oxy-combustion capture

As indicated earlier, oxy-combustion systems for CO_2 capture are not yet commercial and only just entering the pilot plant stage of development. This approach thus poses greater technical risks than pre- or post-combustion systems for full-scale power plant applications at this time. Aside from issues of scale-up, the technical risks for oxyfuel systems include all facets of boiler operation (such as burner design, flue gas recycle and temperature control) as well as downstream systems for flue gas clean-up, dehydration, prevention of air in-leakage and CO_2 compression. Pilot plant tests will provide important data concerning all of these issues, but scale-up to commercial size will pose additional technical risks. The production of oxygen, however, is already commercial, although multiple units would be required to supply the large quantities of oxygen needed for a full-scale power plant.

System integration risks

A technical risk associated with all approaches to power plant CO_2 capture is the "systems level" risk stemming from integration of multiple processes or components, all of which must operate reliably to avoid CO_2 emissions to the atmosphere. At the plant level this refers to integration of the capture unit with other plant components (such as the coupling at a PC plant between an amine system and the steam cycle that provides heat for sorbent regeneration). At a higher level, the systems for transport and storage of captured CO_2 must operate as reliably as the CO_2 capture unit. Experience with CO_2 pipeline transport and underground injection for enhanced oil recovery, as well as more limited international experience with industrial storage projects, indicates that this will not be a problem. But here too there is a need to demonstrate this capability in a power plant setting, where the quantities of CO_2 to be captured, transported and stored are typically several times larger than at current industrial CCS operations.

Based on current system designs, there is also a technical risk that the addition of a CO_2 capture unit could impede the ability of a power plant to generate electricity in the event of a mishap or outage of the CO_2 capture system. For example, if future restrictions on power plant CO_2 emissions specify a maximum allowable quantity of CO_2 per kilowatt-hour of electricity generated, a plant could be forced to shut down if the CO_2 unit malfunctioned. Such a risk would depend on details of the regulation, such as its specified averaging time and the provision of exemptions for special circumstances. Restrictions in the form of an annual cap on CO_2 emissions offer more flexibility since they allow a specified release of CO_2 each year, either on a planned or unplanned basis. Higher emissions during one period could then be compensated by lower emissions at a later time. In all cases, plant designs that allow for a bypassing of the CO_2 capture unit may be desirable, especially at early installations, until the reliability of CO_2 capture is proven in large-scale power plant operations.

4.2 Health, safety and environmental risks

This category encompasses risks to the health and safety of workers at power plants equipped with CO_2 capture systems, as well as any risks to the public from chemical or other releases to the environment resulting from use of CO_2 capture technology.

In general, the health and safety risks of CO_2 capture systems are expected to be the same or similar to those of technologies currently in widespread use at power plants and other industrial facilities. For example, each type of capture system brings with it a set of risks related to the handling, storage and use of chemicals and by-products associated with that particular technology. Such risks span a range of common industrial considerations such as the potential for spillage, leakage, flammability and worker exposure. Considerations unique to post-combustion systems include the handling of reagents such as amines or ammonia and their chemical by-products or wastes. For oxy-combustion systems there are unique risks associated with large-scale oxygen production, while for pre-combustion systems there are risks associated with the production and use of hydrogen for power generation. And of course, all capture systems introduce risks associated with the production and handling of large volumes of concentrated CO_2.

In general, all of the risks outlined above are currently well-understood since they are common to a broad range of industrial processes and situations for which codes, standards, operating procedures, worker training programmes and other measures have been developed to minimise or eliminate risks based on decades of past experience. Studies by the Intergovernmental Panel on Climate Change [IPCC, 2005] and the World Resources Institute [WRI, 2008], among others, have noted that, while industrial process operations are never completely risk-free, the *added* health and safety risks associated with commercial CO_2 capture processes are likely to be small to negligible. Of course, such expectations remain to be confirmed by future experience at power plants employing capture technologies on a significant scale.

The environmental risks of CO_2 capture depend on the type of capture system employed. Amine-based post-combustion systems may introduce a number of direct and indirect environmental risks that must be evaluated. Direct risks could result from process emissions to the air and land. For example, the chemical reactions that capture and release CO_2 also generate small amounts of ammonia that can enter the flue gas stream and be released to the atmosphere. Trace quantities of MEA or other amines also might be emitted if entrained in the flue gas stream. Data are needed to determine whether such emissions occur and, if so, at what levels. Similar assessments are needed to characterise the environmental risk, if any, from solid wastes that are formed with spent sorbent. In the US, for example, spent solids from some current amine systems are classified as a hazardous waste, requiring special procedures for transport and disposal [Rao and Rubin, 2002].

Indirect environmental risks from CO_2 capture systems may result from system-wide changes in mass and energy flows when a capture unit is added to a power plant. In particular, the energy requirements for capture and compression of CO_2 reduce the net efficiency of the plant, so that greater quantities of fuel and chemical reagents are needed *per unit of electricity generated* compared to a similar plant without CO_2 capture. This affects the rate of environmental emissions across the life cycle of the facility. Some emission rates will increase (e.g., plant-level fuel flow and solid wastes) while others decrease as a result of the CO_2 capture unit (e.g., CO_2 and other air pollutants). Currently, such indirect effects are greatest for post-combustion capture because the energy requirement of current amine-based systems is nearly twice that of current pre-combustion capture [Rubin et al., 2007a].

It is important to note, however, that the environmental risks of indirect impacts can only be assessed properly in the context of a particular situation. For example, if a modern efficient power plant with CO_2 capture replaces an old inefficient unit without capture, the net effect could be a reduction in *all* environmental emissions. Similarly, overall coal use in a carbon-constrained world with CO_2 capture systems may be lower than projected levels without carbon constraints, so that net fuel cycle impacts are reduced, despite the energy “penalty” for CO_2 capture. In general, any process improvements that reduce the energy required for CO_2 capture and compression will reduce indirect environmental risks.

4.3 Economic and financial risks

Here we outline several types of economic and financial risks associated with the use of CO_2 capture systems. These stem mainly from the technical risks described earlier, as well as from other factors that are discussed.

Risks for initial capture projects

The cost of a CO_2 capture system represents a substantial investment that will increase the cost of a new power plant by roughly 50 to 80% [NETL, 2007].

Large-scale CO_2 capture projects thus face a risk when seeking financing because the initial (first-of-a-kind) commercial projects do not yet have a track record of proven costs and reliability. For example, the total cost of installing and operating CCS at a 400 MW coal plant for the first five years is estimated to be nearly US$1 billion [Pew Center, 2007]. Such projects are typically paid for through a combination of debt and equity financing. In a market economy, however, financial institutions may be averse to providing the large amounts of capital needed, especially for technologies with no prior history. For projects that do receive financing, investors typically demand a risk premium for newer technologies. This is reflected as a higher rate of return (or interest rate), which increases the overall project cost. That premium is likely to be greatest for pre-combustion capture projects on IGCC plants since such systems are not yet prevalent in power plant applications and are thus perceived to be riskier than conventional combustion-based plants. In cases where project financing is provided wholly or in part by a government agency, a risk premium may or may not apply. In such cases, however, the increased financial risk for early commercial projects is borne by the government.

A second type of risk is the potential for cost escalations due to unforeseen problems [Rubin, et al., 2007b]. This is the economic ramification of the technical risks described earlier. Despite careful and confident planning, including the provision of “contingency costs” in the project budget, early commercial projects often encounter problems that prove more difficult and costly to correct. Where this occurs, additional financing may be needed or the project scope modified to correct the situation. Resulting delays with limited or no service may incur additional costs for purchased power and interest on debt.

A third type of economic risk, faced by all construction projects, is the potential for an escalation in the cost of equipment, materials, or labour specified for the installation. Dramatic increases of this type were seen recently in virtually all areas of industrial construction from 2004 to 2008. Uncertainties remain as to future trends in the face of the current worldwide economic slowdown.

Figure 8 graphically depicts the cost risk of a new technology. In general, cost tends to rise as a technology moves from research and development to commercialisation. Costs later decline as a technology is more widely deployed and matures. Large-scale CO_2 capture projects at power plants are currently entering the demonstration phase on this curve. Thus, initial projects are likely to be more costly than later ones, which will benefit from initial experience and employ less conservative designs. The magnitude of cost risks can vary widely.

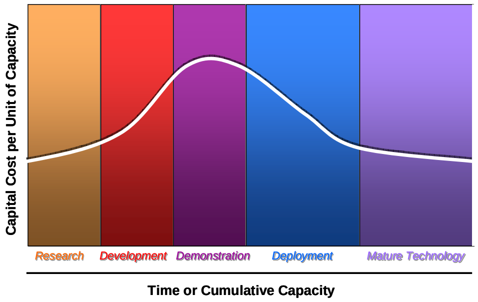

Figure 8. *Typical cost trend for a technology as it develops from early stages of R&D to demonstration, commercialisation and deployment. Initial cost estimates may be higher or lower than mature costs. (Source: adapted from [Dalton, 2008]*)

Carbon market risks

The widespread deployment of carbon capture technologies may come about in either of two ways. One is a regulatory requirement or performance standard that effectively mandates the use of CCS. To date such a regulation exists only in the UK, although standards of this type have been proposed and are under consideration in other countries[5]. The other is a market response to a price on carbon emissions established via a carbon tax or a cap-and-trade programme such as the European Union Greenhouse Gas Emission Trading System (EU ETS). If the price on carbon emissions is sufficiently high, installation of a carbon capture system can be more economical than buying allowances (or paying a tax) to emit CO_2.

In a carbon market of this type, the economic risk facing a utility company is whether – or when – to install CO_2 capture. Market prices for CO_2 (where they exist) have been well below the cost of a CO_2 capture system (e.g., in the neighbourhood of US$20 per tonne of CO_2 in the EU ETS as of mid-2009). Future carbon prices are expected to be higher as the cap on CO_2 emissions becomes more stringent. However, if the higher carbon prices needed to justify the cost of a CCS system (currently estimated in the range of US$50 to 100 per tonne of CO_2 avoided) [Rubin, 2008] fail to materialise, power plant owners who install CCS in anticipation of higher prices could end up paying more to control CO_2 emissions than if they had simply paid the carbon price. On the other hand, if carbon prices rise faster than expected, or if technology innovations substantially reduce the cost of carbon capture, a failure to adopt the technology could prove costly.

The two key factors affecting risk, therefore, are the future carbon price and the future cost of CCS for different power plant applications. The former will depend largely on the severity of the annual CO_2 limit under a cap-and-trade policy, while the latter is dominated by the cost of the CO_2 capture system. Both of these variables will likely change over time.

Economic risks to society

Besides the economic and financial risks to utility companies, there are also economic risks to society as a whole in failing to adopt CO_2 capture and sequestration as a GHG mitigation measure for power plants. A variety of energy-economic modelling studies have estimated the cost of stabilising the atmospheric concentration of GHGs at different levels, with and without the availability of CCS. Figure 9 shows results from one recent study, which concluded that the global cost of meeting climate goals could be up to US$5 trillion (roughly 40%) higher without CCS in the mix of available mitigation options. These studies also conclude that

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[5] On November 9, 2009 the UK government announced that “with immediate effect, to gain development consent all new coal plant will have to show that they will demonstrate the full CCS chain (capture, transport and storage) from the outset on at least 300 MW net of their total output”. Government support for four such CCS projects is anticipated [DECC, 2009].

stabilisation goals of 450 ppm CO_2 equivalent or less – goals that some believe are necessary to avoid serious climate change impacts – are simply not achievable without CCS, even assuming immediate action [EMF, 2009].[6]

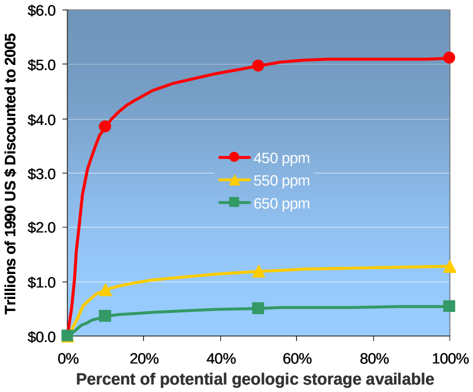

Figure 9. *The economic value of CCS is shown as the reduction in total global cost of meeting each of three climate stabilisation levels (450, 550, 650 ppm CO_2 equivalent) with CCS available at three levels of geological sequestration potential (10%, 50% and 100% of estimated technical potential). (Source: [Edmonds, 2008])*

4.4 Legal and regulatory risks

The technical and economic risks associated with power plant CO_2 capture derive fundamentally from the legal and regulatory risks facing fossil fuel power plants. Without a strong regulatory policy driver, there would be no need for or interest in CO_2 capture. Thus, the current interest in CO_2 capture systems is driven mainly by the expectation that power plants will become subject to stringent carbon constraints at some point in the future. Although coal-fired plants are the main focus of concern, units burning natural gas face similar risks. At the present time, legal and regulatory risks of CCS are a concern mainly in the US, the European Union (EU) and other industrialised countries that plan to adopt new GHG reduction measures affecting power plants. Emerging economies such as China and India, which account for a large and growing share of global CO_2 emissions from coal, have not yet reached that stage. However, they are closely following CCS developments and are involved in capture-related research and development [CSLF, 2009].

Uncertain capture requirements

Carbon reduction requirements, as noted earlier, may come in the form of a market-based cap-and-trade programme, or in the form of regulations that stipulate a reduction level or a maximum allowable CO_2 emission rate (performance standard). In general, the more stringent the emission reduction, the greater are the technical and economic risks to power utilities that rely on fossil fuels. Faced with stringent requirements, companies must decide whether to deploy commercially available CO_2 capture systems, or switch to some other technology such as a non-fossil energy source.

As noted above, carbon market prices in the EU ETS have been well below the cost of CO_2 capture, as have the initial carbon prices in proposed US legislation for a cap-and-trade system [Pew Center, 2008]. Thus, without additional incentives it does not appear likely that carbon markets will create a demand for CCS in the

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[6] There are also economic risks to society associated with failing to take adequate actions to mitigate global climate change, including failure to adopt CCS where needed. Discussions of such risks are beyond the scope of this report but are addressed elsewhere (e.g., [IPCC, 2007b]).

near future. For that reason, recent legislative proposals in the US have included bonus allowances for early deployment of CCS under a cap-and-trade system.

For example, the 2009 Waxman-Markey bill would provide additional allowances valued at US$50 to 90 per ton of CO_2 avoided for the first 6 GW of cumulative generating capacity capturing and storing at least 50% of its emissions. Bonus allowances at lower prices would be available for an additional 66 GW of generating capacity under this bill [H.R.2454, 2009].

Another nearer-term driver for CCS may be a regulatory requirement such as a CO_2 performance standard that requires some level of CO_2 capture for new plants. Some existing units also could be affected. For example, in the US, the State of California introduced in 2006 a CO_2 performance standard for coal plant CO_2 emissions that has since been adopted by several other western states. The California law prohibits load-serving entities and publicly-owned utilities from entering into long-term financial commitments for baseload power unless the power provided meets an emission standard that is "no higher than the GHG emissions levels of a combined-cycle natural gas turbine" [Pew Center, 2008]. That emission level was set conservatively at 1,100 pounds of CO_2 per megawatt-hour (lbs/MWh) of electricity produced (500kg CO_2/MWh). Meeting that emission level at an efficient new coal plant would require a reduction in CO_2 emissions per MWh of roughly 30 to 40% – a reduction that could only be achieved by the application of CCS technology. Since current technology can capture up to about 90% of the CO_2, a modern coal-fired power plant could meet the California standard by capturing 90% of the CO_2 from only a portion (roughly half) of the flue gas, as depicted in Figure 10. The smaller treatment unit would significantly reduce the overall cost of installing and operating a CCS system, thus reducing some of the financial and economic risks described earlier.

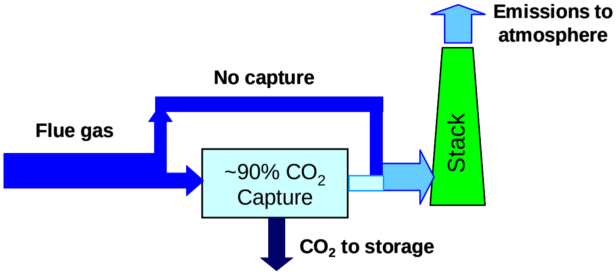

Figure 10. *To meet the California performance standard a power plant could install an efficient CO_2 capture unit on just a portion of the flue gas stream, as depicted in this sketch. This is less costly than treating the entire flue gas stream.*

Other proposed performance standards have been more stringent. Two nationwide bills introduced in the US Congress in 2008 would have limited emissions from all new coal-fuelled power plants to 250 to 285 lbs CO_2/MWh (114 to 130 kg/MWh) – levels that would require CCS systems that capture approximately 85% to 90% of the CO_2 generated [Pew Center, 2008]. Coal-based plants would then be substantially cleaner (in terms of CO_2) than the most efficient NGCC plants, which emit roughly 800 lbs CO_2/MWh (360 kg/MWh). NGCC plants thus also face a risk of future regulations requiring some degree of CO_2 capture to create a "level playing field".

In passing the Waxman-Markey bill in June 2009, the US House of Representatives approved a climate policy measure that includes a less stringent CO_2 performance standard as a complement to an economy-wide cap-and-trade programme. New coal-fuelled power plants permitted between 2009 and 2019 would have to reduce emissions by 50%, but not until capture with geological storage is demonstrated at a specified number and size of plants. Power plants permitted as of 2020 would be required to reduce their annual CO_2 emissions by 65%. After 2025 the US Environmental Protection Agency (USEPA) could promulgate a more stringent standard after appropriate review [H.R.2454, 2009]. At the time of writing, the US Senate is developing its own proposals for CCS, while the USEPA is considering options for a CO_2 performance standard under current US law. Within the EU, the European Parliament has recently discussed CO_2 performance standards for power plants, although proposals to add such standards to the CCS Directive have yet to be adopted. The UK, however, recently adopted a measure that requires any proposed new coal-fired plant to employ CCS on at least 300 MW of the net plant output in order to gain approval for development. Introduced in November 2009, the measure is effective immediately [DECC, 2009].

In summary, there remains considerable uncertainty regarding future requirements for CO_2 emission reductions from fossil fuel power plants, both new and existing. The near-term carbon prices under recent cap-and-trade proposals in the US and Europe would not provide sufficient economic incentives to deploy CO_2 capture systems without additional financial incentives such as bonus allowances for early CCS deployment. Proposed complementary policies in the US would establish CO_2 emission standards for new plants that would require a CO_2 capture system for compliance. Although some proposals would require stringent (85 to 90%) emission reductions, the leading proposal would require only 50 to 65% reductions for installations over the next fifteen years. However, until firm requirements are established by laws and regulations, uncertainties and associated risks will remain.

Uncertain time frame for compliance

Closely related to uncertainty in emission reduction requirements is the uncertainty regarding when CO_2 capture systems might be required. This poses additional risk for electric utility companies. In general, the shorter the time available for deploying CCS the greater are the technical and economic risks discussed earlier.

Roughly a decade or so is typically needed to resolve technical uncertainties and gain confidence with new power plant technologies, and to begin reducing their costs. For these reasons, the leading US regulatory proposal described above requires only a partial degree of CO_2 capture for initial installations over the next decade. Other leading proposals, especially in Europe, advocate that new plants be designed only as “capture ready” until CCS technology is proven for widespread use. This concept requires an explicit definition of what constitutes capture-ready for different types of power plants (PC, NGCC and IGCC). While several studies have examined this issue, no major legislative body has yet codified or imposed such proposals.

R&D organisations such as the US Department of Energy (USDOE) and the Electric Power Research Institute (EPRI) also envision a decade-long time frame before CCS is fully proven for commercial deployment (see Figure 11).

In general, the risks of greatest concern are those associated with the geological storage of captured CO_2 (addressed in IRGC’s policy brief “Regulation of Carbon Capture and Storage” [IRGC, 2008]) rather than the capture system itself. Still, a period of at least five years is needed to build and operate an integrated CCS system at full commercial scale in order to evaluate all risks.

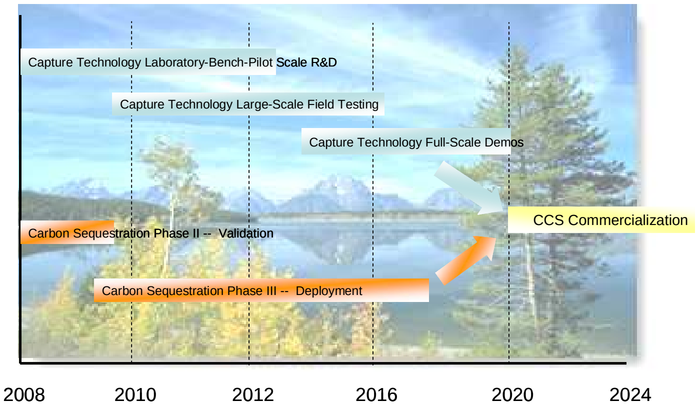

Figure 11. *US Department of Energy (USDOE) roadmap for developing and demonstrating power plant* CO_2 *capture and storage technology leading to commercialisation in 2020 (Source: [Ciferno, 2009])*

Notwithstanding the roadmaps offered by technology developers, policymakers often desire to accelerate the use of pollution control technologies to address environmental concerns. Thus, the time frame for deploying CCS could be faster than recommended by the affected industries. This uncertainty in time frame poses another risk related to power plant CO_2 capture systems.

Uncertain legal liabilities

Another type of legal risk is the penalty for failing to comply with any future requirements for power plant CO_2 capture. The nature of such penalties is not currently known, and would certainly vary by country or jurisdiction. In the US, for example, penalties for violating current air pollution control regulations range from monetary payments (fines) to jail terms for corporate officers.

Because CO_2 capture is a new technology not currently used at power plants, penalties governing initial installations would be expected take into account the low level of maturity of such facilities. Nevertheless, until such liabilities are actually defined they remain another source of risk at the present time.

4.5 Public acceptance risks

Public acceptance of CCS poses an overarching risk that can influence all the other types of risks described above.

To date, public concerns have focussed mainly on the health and safety risks of geological storage of CO_2 and the construction of CO_2 pipelines, rather than on the risks of CO_2 capture systems *per se*. Nonetheless, the installation of carbon capture technologies will require some level of public acceptance, particularly near the site. The public acceptability of capture technologies will be heavily influenced by the safety and performance of the first few sites.

Public awareness of CCS is currently low. There is already some opposition to CCS [Greenpeace, 2008] and more generally to the continued use of coal in electricity generation. Were this to translate into a lack of public acceptance of CCS, the viability of CCS as an emission abatement strategy would be threatened. A lack of public confidence also may result in more stringent legal and regulatory requirements, leading to delays and higher costs that would discourage the use of capture technologies.

5. Risk governance structures and processes

As a society, we look to various public and private organisations to identify and manage the risks associated with industrial technologies. In the context of electric power plants, the institutions, both public and private, that have evolved in industrialised countries over the past century have, in general, provided increasing levels of safety and reliability, as well as substantial progress in reducing the environmental risks associated with electric power generation.

Today, fossil-fuel power plants in most countries are equipped with devices that control (to varying degrees) the emission of harmful pollutants to the environment. The addition of CO_2 capture to this suite of emission control technologies is intended to further reduce environmental impacts – specifically, those associated with global climate change. In terms of risk governance, the institutional structures and processes already in place for other environmental technologies also apply to CO_2 capture systems. Indeed, as an emission control technology, a CO_2 capture system (and its associated risks) is very much like other power plant technologies used to capture conventional air pollutants such as particulate matter and SO_2.

What distinguishes CO_2 capture at this time is its lower level of maturity in power plant applications (hence, greater risks), plus the fact that disposal of captured CO_2 differs from the disposal of conventional power plant wastes (which are recycled to some extent, or contained in landfills rather than injected deep underground, as with CO_2). It is the latter feature – the fact that CO_2 capture is part of an integrated CCS system that includes pipeline transport and geological storage – that adds a new dimension to risk governance structures for capture technologies.

Because institutional structures and processes vary from one country to another (and often within a country), this note provides only a broad picture of the kinds of risk governance structures that are commonly found in the industrialised world.

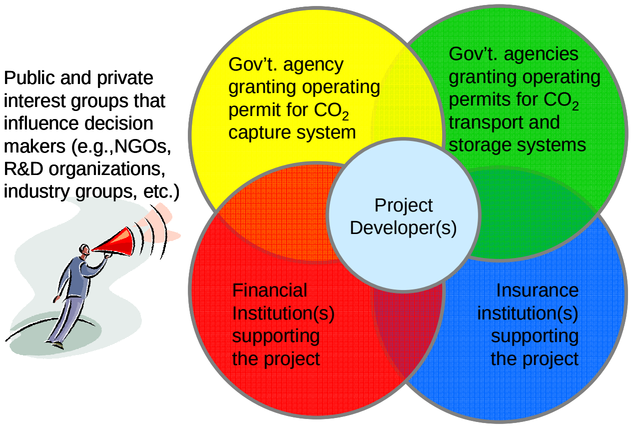

Figure 12. *Schematic of the major actors involved in the risk governance of CO_2 capture systems.*

Figure 12 depicts some of the major institutional actors involved in assessing and managing the risks of CO_2 capture systems. In general, government agencies have the primary role in assessing risks to public health (including workers) and for taking actions to reduce or eliminate significant risks. For CO_2 capture systems, as with other emission control technologies, an operating permit is typically required, granting government approval for use of the device – and thus implying an acceptable level of risk (if any) for the specified operating conditions. Different government agencies may be responsible for granting operating permits for the CO_2 transport and storage components downstream of the capture process. These operating permits might stipulate, among other things, the required level of CO_2 purity and the maximum levels of other gases (impurities) that can be present in the pipeline and/or injection wells. Such restrictions could, in turn, affect the design and permitting of the CO_2 capture system.

As depicted in Figure 12, financial institutions and insurance companies also play a role in risk governance. These (usually non-governmental) organisations are typically sought by project developers to share, or assume, the financial risks and liabilities described earlier. As such, lending agencies and insurance companies are especially involved in assessing the risks of proposed CO_2 capture projects.

Finally, an array of other interest groups and organisations (public as well as private) play an indirect role in risk governance via the influence and information provided to the key governmental and private decision-makers that directly control or govern CO_2 capture projects. While the role and influence of such groups varies from country to country, it can be an important element in risk governance processes.

6. Risk governance deficits for CO_2 capture

Risk governance systems are seldom perfect. For example, despite significant progress in reducing the health and ecological impacts of air pollution from power plants and other sources, the impacts and risks of greenhouse gas emissions linked to global climate change have yet to be controlled.

As defined by IRGC, risk governance deficits are “deficiencies (where elements are lacking) or failures (where actions are not taken or prove unsuccessful) in risk governance structures and processes. They hinder a fair and efficient risk governance process” [IRGC, 2009]. Such deficits represent shortcomings that can, in principle, be remedied or mitigated. They are grouped by IRGC into two broad clusters, namely, (1) deficits in assessing and understanding risks, and (2) deficits in risk management. Within each category IRGC has identified a number of common and recurring deficits, summarised in Table 1.

Table 1. *Summary of common risk governance deficits identified by IRGC. (Numbers in parenthesis refer to IRGC designations.) (Source: [IRGC, 2009]).*

Cluster A: Assessing and understanding risks	**Cluster B: Managing risks**
Gathering and interpreting knowledge	***The preparation and decision process for risk management strategies and policies***
A1: Early warning systems Missing, ignoring or exaggerating early signals of risk	**B2: Designing effective risk management strategies** Failure to design risk management strategies that adequately balance alternatives
A2: Factual knowledge about risks The lack of adequate knowledge about a hazard, including the probabilities of various events and the associated economic, human health, environmental and societal consequences	**B3: Considering a reasonable range of risk management options** Failure to consider a reasonable range of risk management options (and their negative or positive consequences) in order to meet set objectives
A3: Perceptions of risk, including their determinants and consequences The lack of adequate knowledge about values, beliefs and interests and therefore about how risks are perceived by stakeholders	**B4: Designing efficient and equitable risk management policies** Inappropriate risk management occurs when benefits and costs are not balanced in an efficient and equitable manner
Disputed or potentially biased or subjective knowledge	**B6: Anticipating side effects of risk management** Failure to anticipate, monitor and react to the outcomes of a risk management decision in the case of negative side effects
A4: Stakeholder involvement Failure to adequately identify and involve relevant stakeholders in risk assessment, in order to improve information input and confer legitimacy on the process	**B7: Reconciling time horizons** An inability to reconcile the time frame of the risk with the time frames of decision-making and incentive schemes
A5: Evaluating the acceptability of the risk Failure to consider variables that influence risk appetite and risk acceptance	**B8: Balancing transparency and confidentiality** Failure to balance two of the necessary requirements of decision-making: transparency, which can foster stakeholder trust; and confidentiality, which can protect security and maintain incentives for innovation

A6: Misrepresenting information about risk The provision of biased, selective or incomplete information	***Formulating responses, resolving conflicts and deciding to act***
Knowledge related to systems and their complexity	**B1: Responding to early warnings** Failure of managers to respond and take action when risk assessors have determined from early signals that a risk is emerging
A7: Understanding complex systems A lack of appreciation or understanding of the potentially multiple dimensions of a risk and of how interconnected risk systems can entail complex and sometimes unforeseeable interactions	**B11: Dealing with commons problems and externalities** A lack of understanding of the complex nature of commons problems and consequently also of the specific risk management tools required to address them
A8: Recognising fundamental or rapid changes in systems Failure to re-assess in a timely manner fast and/or fundamental changes occurring in risk systems	**B12: Managing conflicts of interests, beliefs, values and ideologies** A conflict may be negotiable or irreconcilable, and risk managers must have the capacity to distinguish between the two
A9: The use of formal models An over- or under-reliance on models and/or a failure to recognise that models are simplified approximations of reality and thus can be fallible	**B13: Acting in the face of the unexpected** Insufficient flexibility in the face of unexpected risk situations
Knowledge and understanding are never complete or adequate	***Organisational capacities for responding and monitoring***
A10: Assessing potential surprises Failure to overcome cognitive barriers to imagining events outside of accepted paradigms (“black swans”)	**B5: Implementing and enforcing risk management decisions** Failure to muster the necessary will and resources to implement risk management policies and decisions
	B9: Organisational capacity Failure to build or maintain an adequate organisational capacity to manage risk
	B10: Dealing with dispersed responsibilities Failure of the multiple departments or organisations responsible for a risk’s management to act cohesively

In the context of CO_2 capture technologies, risk governance deficits can be found in both clusters. While a comprehensive analysis is beyond the scope of this concept note, the sections below identify a number of the major risk governance deficits that currently apply to CO_2 capture systems.

6.1 Deficits in assessing and understanding risks

Several of the deficits relating to knowledge and understanding of risks apply to the various types of CO_2 capture systems proposed for use at power plants. The most common are outlined below. Note that both the public and private organisations depicted in Figure 12 (page 23) may suffer from these deficits. Also, because risk assessment processes and institutions vary across the globe, the precise nature and extent of such deficits also may vary from place to place.

Factual knowledge about risks (A2)

This deficit is arguably the most pervasive and most important of the several in this cluster. Assessments and understanding in the three major categories of risk discussed earlier for CO_2 capture systems – technical risks; health, safety and environmental risks; and, economic and financial risks – all suffer from inadequate knowledge of the probability and consequences of adverse technical, environmental and economic outcomes when CO_2 capture systems are fitted to large commercial power plants. Although data are available for commercial capture technologies employed in other industrial applications, and at smaller scales, extrapolations to full-scale power plants remain uncertain at this time. Until a number of full-scale demonstrations are carried out using a variety of capture technologies in a variety of power plants (including combustion and gasification-based systems, different fuel types, and new as well as existing plants), the knowledge-base will remain inadequate for rigorous risk assessments.

Knowledge of stakeholder perceptions (A3)

In contrast to the deficit above, which relates to knowledge of the probabilities and consequences of adverse events, this deficit relates to "knowing and understanding how risks are perceived by non-scientific publics, including ordinary citizens, business managers, representatives of stakeholder groups and politicians" [IRGC, 2009]. In this regard, many of the current programmes related to CO_2 capture – and to CCS more broadly – have indeed included efforts to involve stakeholders in plans for technology development. Examples include the efforts of the Carbon Sequestration Leadership Forum (CSLF) and other national and international initiatives. Nevertheless, such efforts do not appear to have been adequate in light of the failure to anticipate public opposition that led, for example, to the cancellation of one large CCS project in the US (the Carson City IGCC project at Long Beach, California), and more recent opposition to projects in the Netherlands and Germany [BW, 2009; WSJ, 2009]. Public concerns in these cases focussed mainly on the environmental, health and safety risks of CO_2 pipelines and the underground sequestration of CO_2 rather than the CO_2 capture systems. Nonetheless, such cases suggest that current efforts to elicit the perceptions of key stakeholders may not be adequate in all cases.

Evaluating risk acceptability (A5)

Risk governance deficits in this area refer to cases in which there has been inadequate attention paid to understanding stakeholder perceptions and values, or to defining and understanding the degree of risk aversion and risk tolerance of key organisations and stakeholders. Of particular relevance to CO_2 capture systems are the environmental risks of CO_2 emissions to the atmosphere, the environmental, health and safety risks of intended and unintended chemical releases from CO_2 capture systems, and the economic and financial risks associated with installations of large-scale capture units at power plants. Here too, the nature and degree of such deficits may vary from country to country or even from one project to another (depending upon the risk of concern).

Understanding complex systems (A7)

In assessing CO_2 capture system risks, it is imperative to also understand all relevant linkages to the CO_2 transport and storage components of an integrated CCS project. As noted earlier, those downstream components can affect the design, cost and operation (hence, risks) of the capture unit at a given facility. In a larger sense, an assessment of CO_2 capture system risks, especially environmental and economic risks, also requires an understanding of the role of CO_2 capture in national and global programmes and strategies to reduce GHG emissions. For example, a full assessment of economic risks would require knowledge about the potential to sell excess CO_2 emission allowances if an efficient CCS system is installed. These are but a few examples of complex systems in which CO_2 capture technologies are embedded. While much progress has been made in understanding these complexities and their interactions (via technical analysis and systems modelling), full and reliable understanding, especially of the role of CCS in climate policy, remains a challenge.

6.2 Deficits in managing risks

The risk governance deficits listed in Cluster B of Table 1 apply when there is a lack of capacity to set goals, develop and evaluate a range of risk management options, consult stakeholders, balance efficiency and equity, make and implement policies and decisions, resolve conflicts, or evaluate and monitor the results of decisions based on actual experience [IRGC, 2009]. The most common deficits in this cluster with regard to power plant CO_2 capture systems are outlined below. Again we note that the specific nature and extent of these deficits may vary from place to place.

Designing effective risk management strategies (B2)

Despite widespread belief in the international community that CO_2 capture and storage must play a critical role in any cost-effective strategy to address global climate change, at present only the UK appears to have a binding requirement to capture CO_2 at power plants. While a number of demonstration projects and programmes have been proposed, there are not yet any firm financial commitments to build and operate full-scale capture units (several hundred megawatts or more) to demonstrate the viability of the technology in electric utility applications, especially coal-fired power plants[7]. Thus, there is a need for more effective strategies to manage not only the technical and environmental risks of CO_2 capture, but also the legal and regulatory risks (described earlier) that stem from current uncertainties as to future requirements or incentives for the use of CO_2 capture at power plants.

Considering a range of options (B3)

To effectively manage the several types of risks related to power plant CO_2 capture, policies and actions are needed on two key fronts: construction of several full-scale demonstration projects; and, clarity with respect to the nature of future requirements and/or incentives to deploy CO_2 capture systems. In both cases a range of options should be identified and evaluated in the context of a particular national or regional situation. While this has occurred to some extent in some locations, deficits remain. For example, the need for large-scale demonstration projects – which has been widely recognised for many years – has languished for lack of adequate measures to fund and launch such projects. Similarly, there has been relatively little consideration of a range of policy options for capture technology deployment to combat climate change. By far the dominant option for reducing CO_2 emissions has been a market-based approach in which a carbon price is relied on to trigger appropriate mitigation responses that may (or may not) include power plant CO_2 capture systems. Other policy options, such as mandatory

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[7] A number of countries, including Australia, Canada, China, UK and US as well as the European Commission have announced plans for large-scale demonstrations of CCS at coal-based power plants. In some cases partial funding has been authorised as part of a cost-shared government-industry programme. However, as of September 2009, there are still no firm commitments ("money in a lock-box") for full funding of these projects (estimated to be roughly US$1 billion per project), nor firm guarantees that they will materialise.

CO_2 performance standards or portfolio standards for new and existing power plants, or options involving a mix of policy approaches, have received comparatively little attention to date. Failure to consider a reasonable range of options is a deficit that can lead to inefficient or ineffective outcomes for risk management.

Reconciling time horizons (B7)

This deficit has to do with “a tendency to ignore long-term risks and costs relative to the day-to-day needs that seem to be – and sometimes are – urgent” [IRGC 2009]. This deficit arguably applies to climate change mitigation measures in general, not solely to power plant CO_2 capture systems. Symptomatic of this deficit, however, is the relatively slow pace of progress in demonstrating the viability of capture and storage in full-scale power plant applications – a need that has been recognised and widely promoted by governments, as well as industry, for many years, but which nevertheless remains elusive. For example, current timetables in the EU envision up to twelve such demonstrations within the next five years, but the financing of such projects is contingent on income from a carbon pricing policy that has yet to be implemented. In the US, promises of government funding for large-scale projects are often contingent on annual appropriations by the US Congress, which may or may not materialise. Immediate concerns often slow or prevent actions to address longer-term issues and risks.

Balancing transparency and confidentiality (B8)

Another risk governance deficit that may apply to power plant CO_2 capture systems in some cases is a failure to appropriately balance the public’s need for transparency and openness versus the private need to protect the confidentiality of proprietary data or information. From a public perspective, information concerning the performance, risks and costs of a CO_2 capture system can be important to the development of sound public policies. From a private perspective, technology developers and vendors in a competitive market have a commercial interest in protecting their intellectual property and know-how. Achieving an appropriate balance can be difficult in cases where government funding is provided (or offered) to support technology development or demonstrations. Included in this regard is the sharing of information among different countries involved in CO_2 capture technology development. International accords and widespread adoption of successful best practices can help address this deficit where it occurs.

Dealing with dispersed responsibilities (B10)

Because power plant CO_2 capture systems are part of an integrated process involving CO_2 capture, transport and storage, risk management responsibilities are likely to be dispersed among multiple agencies or levels of government. Typically, separate departments or agencies are responsible for approving the installation and use of power plant capture systems, CO_2 pipelines, and CO_2 injection systems for underground storage. In the US, responsibilities may be shared among federal, state and local branches of government. In Europe, an additional dimension derives from the potential need to transport captured CO_2 between countries, thus involving different national jurisdictions. Independent actions on the part of any one of the separate responsible agencies could affect other components of the CCS system. For example, a failure or delay in permitting a CO_2 pipeline or injection site could affect the cost and financing of the CO_2 capture unit since it is part of the overall system. Risk management organisations thus will require a greater degree of coordination, or perhaps a reorganisation of responsibilities, to deal effectively with all aspect of power plant CO_2 capture and storage systems.

7. Conclusions and recommendations

This concept note has focussed on risks associated with power plant CO_2 capture systems, a key component of carbon capture and storage (CCS) technologies that are expected to play a significant role in controlling GHG emissions from power plants and other large industrial facilities.

The three major types of power plant CO_2 capture systems currently available or under development were described (pre-combustion, post-combustion and oxy-combustion systems), and several categories of risks associated with these systems were identified. These include technical risks; health, safety and environmental risks; economic and financial risks; legal and regulatory risks; and, public perception risks.

To a large extent, the technical risks derive mainly from the current lack of experience in building and operating CO_2 capture systems at the large scale required for power plant applications (especially coal-fired plants), as well as from uncertainty regarding the future availability of lower-cost systems. The level of technical risks associated with oxy-combustion capture is greatest because the technology is only now undergoing testing at the pilot plant scale (about one-fiftieth the size of a full-scale commercial unit). Pre- and post-combustion systems are already commercial at industrial scales.

All three systems also have potential health, safety and environmental risks (both direct and indirect) that must be fully evaluated in the context of power plant operations. This is particularly important for amine-based and other chemical-based post-combustion systems, whose risks are potentially largest.

In terms of economic and financial risks, the cost of a power plant CO_2 capture installation (plus the added costs of transport and storage infrastructure) is known to be high and is likely to be highest for early movers. At the same time, raising the necessary capital may be difficult or more costly because the technology has no proven track record of costs and reliability in full-scale power plant applications.

Legal and regulatory risks, on the other hand, derive mainly from uncertainty as to the timing and nature of future incentives or requirements to deploy CO_2 capture systems at power plants. Governments around the world are considering a range of policy options (such as the establishment of cap-and-trade schemes, carbon taxes, and CO_2 performance standards) which will affect the operating environments of power plants and the electric utility companies that operate them. Since newly-constructed power plants typically operate for 40 years or more, operators and investors desire some level of certainty regarding future regulatory demands in order to effectively plan future generating capacity. In the absence of firm regulatory requirements, utilities building new fossil-fuel plants, for example, must decide whether or not to invest in units that are “capture-ready” since retrofitting a CO_2 capture system is expensive in terms of both capital cost and reduced generating efficiency.

Key actors in the risk governance of CO_2 capture include plant owners and operators, other industry sectors (particularly the financial and insurance sectors), government departments and agencies, the general public and various interest groups. There is also a role for science to bring greater clarity regarding the level of risk for different systems by interpreting the knowledge gained from early technology deployment.

To a large extent, the risk governance processes and institutions that have evolved over past decades have done an effective job of reducing or eliminating many of the prior risks associated with power plant operations. The future need to incorporate CO_2 capture systems into many of those operations to mitigate global climate change introduces new risk governance deficits. This concept note has identified nine such deficits.

In its recent policy brief on carbon capture and storage [IRGC, 2008], IRGC recommended, *inter alia*, the establishment of a regulatory framework that balanced stability and predictability with flexibility and adaptability to new scientific information. IRGC also recommended the rapid establishment of a diverse portfolio of full-scale CCS demonstration plants to provide scientific and technical answers to key concerns.

Given the differences among the three approaches to CO_2 capture, it is essential that demonstration plants include at least two, and preferably more, full-scale applications of each of the three systems at power plants. This will provide the critical information needed to overcome the current lack of factual knowledge about risks (deficit A2) and to better understand the total system of which CO_2 capture is just one part (A7). Ensuring that data and risk estimates are public, and not proprietary, will also help overcome the deficits concerned with public perception (A3) and the acceptability of risk (A5). The responsibility for establishing full-scale demonstration projects lies primarily with national governments, who will probably need to share in the funding of these demonstration projects.

Given the current absence of hard data regarding the risks associated with power plant CO_2 capture technologies, it is crucial that risk management strategies are adaptive, allowing for refinement when such data become available. Existing governance structures and processes (including health and safety legislation and pollution control legislation) already place primary responsibility for risk management on plant operators. During the demonstration and early deployment of CO_2 capture systems, plant operators will need to work with scientists to closely monitor and understand the full range of environmental impacts and risks associated with large-scale CO_2 capture systems. In turn, regulators should be adaptive in setting long-term emission standards only when the results of such evaluations are available. Such an approach would provide an effective risk management strategy (B2), give time and information to consider a reasonable range of options (B3) and balance confidentiality and transparency (B8).

The CCS value chain is complex and risk governance responsibilities will be shared amongst all the actors identified earlier. CO_2 capture systems cannot be isolated from this dispersed network – without their installation the entire CCS process cannot function. Once the technology is widely deployed and used, it is the power plant operators who will have the leading role in risk avoidance by ensuring proper system operation. However, in the crucial early stages, when the technologies are being tested at a relatively small number of power plants, risk governance responsibilities will need to be shared more widely, not least with governments (who have a policy interest in successful deployment of CCS) and scientists (who can provide objective assessments of technological risks). It is crucial that each of these groups understands and fulfils its role within the dispersed governance structure (B10). Existing groups such as the CSLF and the International Energy Agency's (IEA) CCS regulators network can play an important role in facilitating such coordination.

Perhaps the most difficult risk governance deficit to address is that of reconciling time horizons (B7). Meeting the ever-increasing global demand for electricity requires that new plants come on line regularly. It takes several years to plan, finance, build and commission a large power plant and in many parts of the world coal and/or natural gas remain the most economical choice amongst fuel sources. New fossil-fuel power plants built now, if left uncontrolled, will still be emitting CO_2 in 2050 (and perhaps beyond). Meanwhile, many of the world's industrialised nations are becoming increasingly vocal in their calls for action to reduce GHG emissions. Carbon trading schemes are developing in Europe, the US, Australia and elsewhere. The EU and a number of national governments also are signalling their intent to support the introduction of CCS to reduce CO_2 emissions from coal-fired power plants. In this environment, there is potential for the policy time frame to be much shorter than that for commissioning new power plants. In the meanwhile, however, utilities planning new generating capacity must grapple with the current regulatory uncertainty. One solution already introduced in the UK (specific to coal) and under consideration by some other countries is that operating permits for new power plant using fossil fuels be granted only if the plants are built to be "capture-ready" or "CCS-ready" (terms which have been defined in different ways). Another proposal is to require all new as well as existing coal plants to install CCS once the technology has been demonstrated to a specified extent. Yet another approach is to require some level of CCS immediately on all new coal-based plant. All such proposals remain controversial. Governments can best resolve the time horizon issues associated with CO_2 capture by moving swiftly on large-scale demonstrations and the specification of policy requirements for at least the next decade or two.

In summary, with regard to the risk governance of CO_2 capture systems the following recommendations are offered:

Governments should:

- Facilitate and finance, with urgency, the construction of several full-scale power plant demonstration projects using each of the three major capture approaches, so as to acquire the factual knowledge and understanding needed for risk reduction and improved risk management;
- Specify with clarity the nature of future requirements and/or incentives to deploy CO_2 capture and storage (CCS) systems at power plants over the next one to two decades, recognising that subsequent requirements will be determined in an adaptive manner as new information and experience accumulates; and
- Specify the conditions, if any, under which new coal-fired and gas-fired power plants can be built and operated during the next one to two decades without a CO_2 capture system, such as a requirement that all new fossil fuel-based plants be "capture-ready" or "CCS-ready", however those terms are defined.

Regulators should:

- Work with plant operators and scientists to establish an adaptive regulatory framework that allows longer-term regulations to be introduced and modified in light of new knowledge gained from demonstration plants and subsequent technology deployment.

Power plant operators and scientists should:

- Develop measures and a measurement system that provides the maximum learning from demonstration plants and the effective monitoring of all future installed CO_2 capture systems.

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The International Risk Governance Council (IRGC) is an independent organisation based in Switzerland whose purpose is to help the understanding and governance of emerging, systemic global risks. It does this by identifying and drawing on scientific knowledge and the understanding of experts in the public and private sectors to develop fact-based recommendations on risk governance for policymakers.

IRGC's goal is to facilitate a better understanding of risks; of their scientific, political, social, and economic contexts; and of how to manage them. IRGC believes that improvements in risk governance are essential if we are to develop policies that minimise risks and maximise public trust in the processes and structures of risk-related decision-making. A particular concern of IRGC is that important societal opportunities resulting from new technologies are not lost through inadequate risk governance.

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International Risk Governance Council

Chemin de Balexert 9
1219 Châtelaine
Geneva – Switzerland

www.irgc.org

Tel.: +41 22 795 17 30
Fax.: +41 22 795 17 39

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