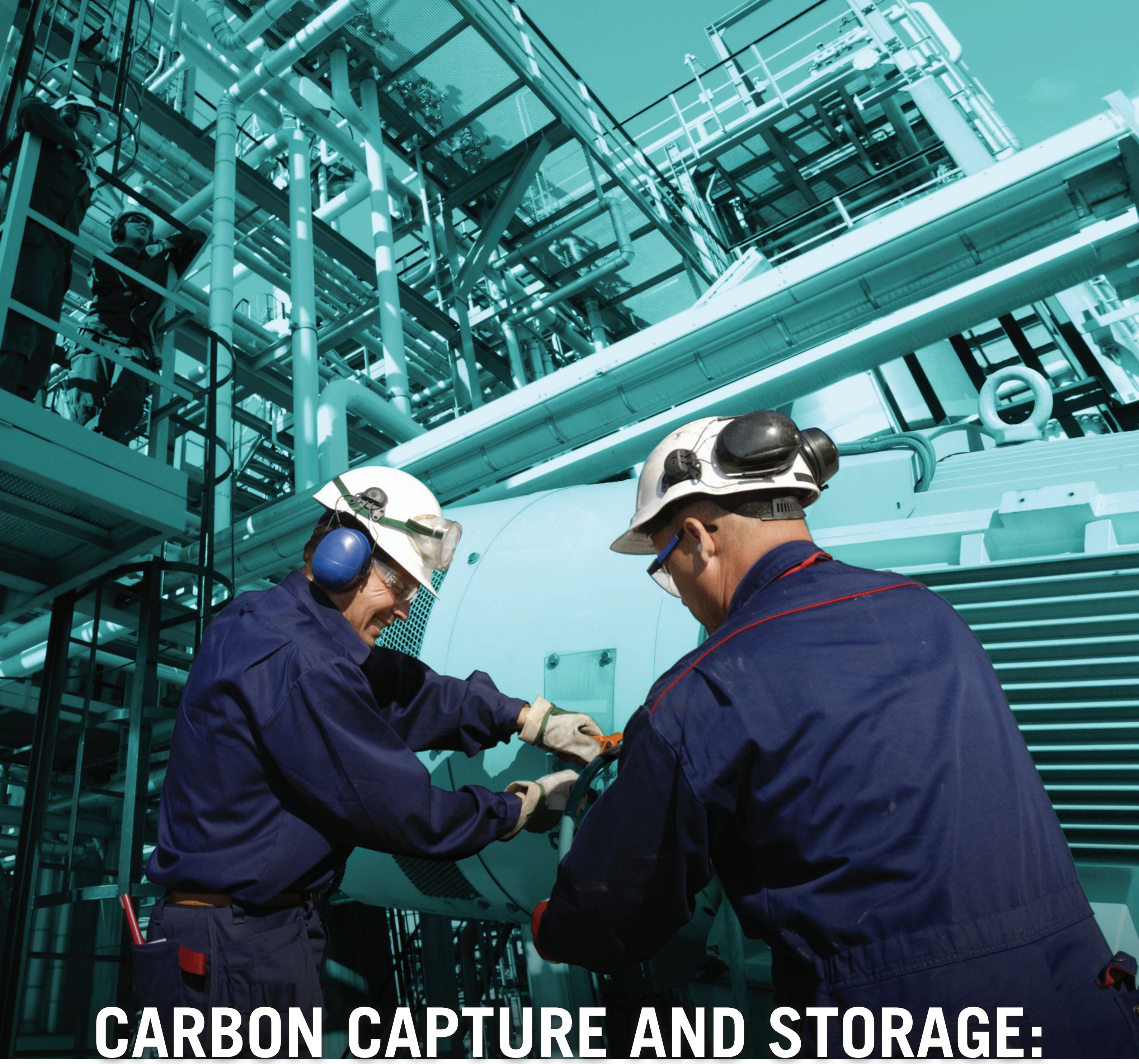

# CARBON CAPTURE AND STORAGE:

## AN APPROACH TO UNDERSTANDING POTENTIAL RISKS AND THEIR COST IMPLICATIONS

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# ACKNOWLEDGEMENTS

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# INTRODUCTION

## KEY POINTS/SUMMARY

An approach has been developed for estimating the financial impacts of certain risks to human health and the environment from CCS projects. This approach consists of a financial simulation model using a combination of site-specific and more generic data.

This approach was tested using a case study based on a proposed CCS project, the Jewett FutureGen project in the United States. Results calculated the average costs associated with the risks for a well-sited and operated CCS project at \$0.15/tonne $CO_2$, which is less than roughly 0.4 per cent of estimated project costs.

This approach is flexible in that it could be applied, with some modification, to other CCS projects. It could also be applied at different stages of a project, although the degree of confidence in the results is commensurate with the quality and specificity of available data. As better and more site-specific data are obtained during project development, confidence in the results would increase.

Carbon capture and storage (CCS) is an important technology that can be used to prevent large quantities of carbon dioxide ($CO_2$) resulting from combustion or chemical processing from being released into the atmosphere. CCS integrates three steps: 1. separation (i.e., capture) of $CO_2$ from the exhaust streams of large sources and compression, if needed, 2. transport of the $CO_2$ to a storage location, typically by pipeline, and 3. injection of the $CO_2$ deep underground for permanent storage in a defined geologic formation. Once in that geologic formation, several well-understood geologic trapping mechanisms serve to keep the $CO_2$ there.

The technologies for each of these steps are already used independently for different purposes in several common industries including natural gas refining, oil and gas production, and the manufacture of chemicals. Ongoing work focuses on improving the cost-effectiveness of capture, integrating the three steps, enhancing our understanding of the storage properties of the geologic formations, and providing reliable information for the development of appropriate commercial practices and government policies.

Any well-sited, well-operated CCS operation should have no incident. However, like any industrial operation, CCS has the potential risk for accidents that could lead to damages to human health or to the environment. Some potential types of damages are well understood in a power plant or oil field operation context, such as damages arising from health-related injuries from routine operations. Other potential damages stemming from the possible release of $CO_2$ are less well understood.

This brochure describes a recent project sponsored by a group of stakeholders involved in CCS to use established financial analysis methods to develop a good understanding of the magnitude, timing, and nature of potential financial impacts of the risks of damages to human health and the environment associated with accidental releases from a CCS project. This analysis is intended to help industry make informed investment decisions, to be useful in the further development of laws and regulations governing CCS, and to better inform the public in whose communities CCS projects may be operated.

This analysis will also be useful in considering policies to address the long-term stewardship of $CO_2$ in geologic formations. CCS projects are long-lived. In a typical large project, $CO_2$ injection might take place over a 30–50 year horizon and the $CO_2$ must stay securely in the formation for much longer. Current or proposed regulations in various jurisdictions typically stipulate that responsibility for a CCS project resides with the developer for a specified period of years after injection ceases and/or until it can be demonstrated that certain criteria have been met. After this demonstration, responsibility may be explicitly transferred to a government body. Uncertainty about the ability to make this demonstration in a specified period of time is a significant up front concern for projects. Developers are concerned about the uncertainty of how long they will have to stay active in the project; the public is concerned about who will be accountable if something goes wrong many years out in the future, and project funders worry about the financial risk from this uncertainty. Both $CO_2$ pipelines and the capture facility must also be operated safely over the entire period they are used.

In an effort to demonstrate how potential financial damages can be estimated, a group of diverse organizations involved in CCS sponsored a project by a leading damages assessment firm, Industrial Economics Incorporated (IEc), to develop and test a method for valuing potential CCS risks. This method applies standard approaches used in the insurance and finance industries for risk assessment. The study estimates the scope, timing, and magnitude of potential financial damages associated with the capture, transport and storage portion of a planned CCS project over a 100-year period, including 50 years of injection and 50 years after the $CO_2$ injection has stopped. This study estimated the monetary costs to address impacts on people and the environment arising from accidental releases; it did not estimate the potential costs from facility construction or routine operation, nor potential costs associated with impacts to workers, business interruption, facility repair or similar private costs internal to the operator such as legal penalties or lawsuits. The final report based on this study was released in June 2012[1].

The analytic method was applied to a set of real-world project plans and data, the Jewett, Texas FutureGen 1.0 project. The Jewett site was selected through open competition as one of four finalist host sites for the FutureGen 1.0 project. Although not selected as the final site, a detailed risk assessment was prepared for the Jewett site. This risk assessment is publicly available and served as the basis for testing the method for estimating potential financial damages from a specific large CCS project.

Although the risk assessment was very detailed, it was developed for the first stage of project development: site selection. Additional site characterization work such as drilling test wells and conducting local surveys would take place if the project moved forward for development. This further work would produce additional and more detailed information that would enable more precise estimates of risks and potential damages. Therefore, after careful review, the sponsors of the damage assessment decided that the analysis would use available data from similar industrial processes to develop a reasonable set of assumptions for the few key data types needed for a comprehensive damages estimation mode but not included in the published Jewett risk assessment.

This analysis indicated that the median estimated financial damages from a well-sited, operated, and closed CCS project at this site would be expected to be approximately US$0.15 per ton of $CO_2$ injected[2]. FutureGen 1.0 project was estimated to cost US$1.8 billion. Using this cost basis as a point of comparison, the magnitude of expected financial damages would be less than 0.4 per cent of original project costs.

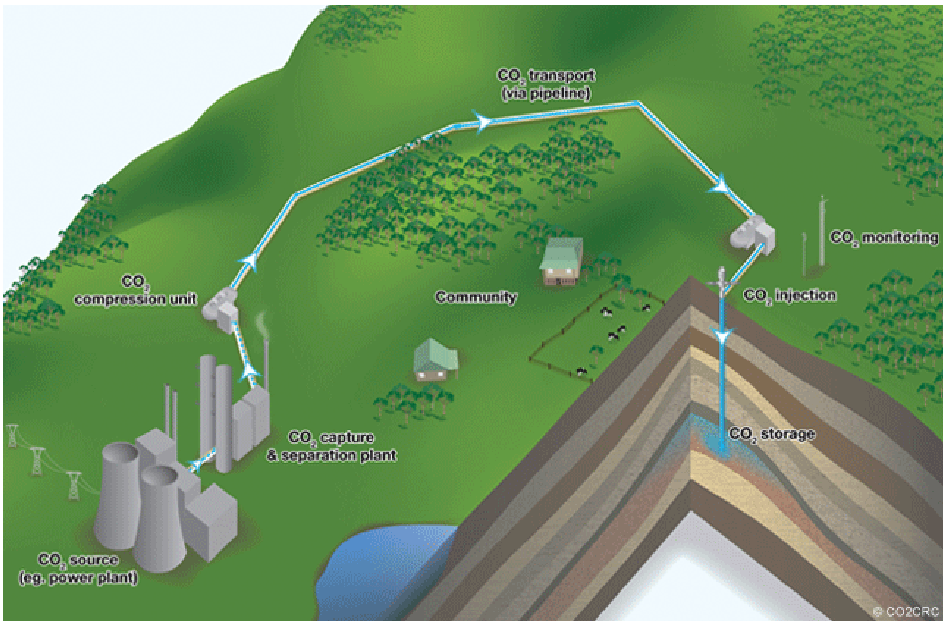



Figure 1: CCS prevents $CO_2$ emissions from entering the atmosphere and instead stores the $CO_2$ deep underground. Source: Global CCS Institute via CO2CRC.

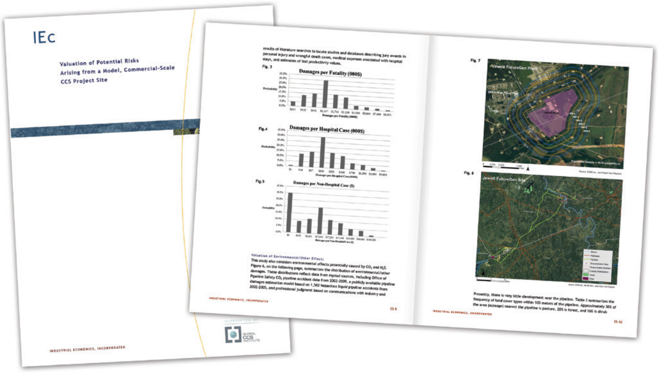
The approach developed in this analysis, fitted to site-specific circumstances and available data, could be applied to other CCS projects. The types of information generated from this approach will be important to several groups. Project developers will be interested in using it early on to develop order-of-magnitude estimates for use in site selection and project design; later, when more detailed site information is available, these same developers can adapt the model to refine their project design and plan risk management strategies. Legislators and regulators will be interested in this kind of information in overseeing public safety and permitting. The financial and insurance industries will use this kind of information in assessing investment risk and designing financial risk management tools. The public will also use this type of information in assessing proposals for CCS projects in their communities.

1 Industrial Economics, Incorporated, “Valuation of Risks Arising from a Model, Commercial-scale CCS Project Site”, Cambridge, MA, June 2012. This report may be downloaded from: http://www.globalccsinstitute.com/campaign/2012/06/valuation-potential-risks-arising-model-commercial-scale-ccs-project-site.

2 The ‘upper end’ (95th percentile) damages estimate was approximately US$0.34 per metric ton.

# HOW DOES THE VALUATION APPROACH WORK?

The approach developed for this study relies on a standard financial modeling procedure called ‘probabilistic simulation’. The steps involved are very briefly described here but are presented in great detail in the IEc report. Essentially, IEc constructed a set of spreadsheets and connected them into a cohesive model. This model was used to generate a very large number of of scenarios that reasonably capture the range of possible outcomes from the modeled project given the underlying probability distributions and variability in impacts and associated damages. The results of the analysis can be used to estimate the probability that various potential damages amounts will be incurred.



### Step 1: Identify Relevant Risk Events

The CCS risk of greatest concern stems from leakage of $CO_2$ at the capture facility, from the pipeline, at the injection well, or from the geologic formation deep underground used for storage. If such a “leakage event” occurs, it could result in human health or ecological harm. Extensive work has been conducted to identify the potential pathways for $CO_2$ leakage. For example, one such effort was spearheaded by the International Energy Agency and resulted in a publicly accessible risk scenarios database for CCS projects[3]. This database contains what is termed ‘Features, Events, and Processes (FEPs)’ related to CCS projects. This database was developed using systems analysis to methodically identify roughly 200 generic FEPs that can be selected on a site-specific basis for use in risk assessment. As discussed in more detail below, this particular application of the model primarily relied on the identification of risk events as presented in a publicly available risk assessment.

### Step 2: Estimate Magnitude and Probability of Risk Events

Standard risk assessments use data from a variety of sources such as equipment manufacturers, historical performance, scientific literature, and site-specific plans to develop quantified estimates of risks. In this case, such data was used to estimate the probability of releases and the likely size of such releases if they occur. These estimates reflect potential ranges of probabilities and sizes of releases. For example, a pipeline rupture could be a small crack that goes undetected for days, thereby releasing smaller amounts of $CO_2$ over a longer period compared to or a large hole that releases $CO_2$ at a greater rate but is detected quickly and stopped. Further, the probability of each of these types of events may be different. Risk assessments often estimate the expected probability of a rupture or similar event that could cause damage, and the expected amount that will be released. The IEc team created a flexible model that allows for both a range of potential events and magnitudes and probabilities that they will occur. Sampled repeatedly and randomly over these ranges, the model estimates the range of possible outcomes.

### Step 3: Develop Cost Relationships Indicating the Range of Potential Costs

IEc evaluated the effects of the potential types and magnitudes of releases identified in Step 2 and developed cost estimates for addressing them based on valuation methods from legal systems for accident compensation, natural resource damage assessments, and cost-benefit studies. In two cases, costs estimates could not be developed from real-world case studies: the cost of $CO_2$ emission allowance prices each year through 2112 (100 years) and the cost of repairing the wellbore in a deep well located at 5000 feet (1524 meters). The project sponsors consulted among themselves and with experts to develop specific assumptions for these variables for use in testing the model.

IEc developed cost curves for each event type that reflect available information and the potential variability in the type and/or magnitudes of underling impacts. For example, the type, number and cost of human health impacts arising from pipeline release will vary depending on the location of the release relative to population centers. The model utilized cost data from a variety of sources, including (but not limited to) court cases, insurance payments, and remediation costs to provide a reasonable range of event-specific costs of damages to human health and the environment.

### Step 4: Combine the Cost Relationships into an Integrated Model

IEc combined the data and relationships developed in the previous steps into an integrated spreadsheet model that generates damage estimates based on a random sampling of the underlying probability distributions and cost curves across all potential events

3 IEAGHG Risk Scenarios Database found online at: http://www.ieaghg.org/index.php?/20091223132/risk-scenarios-database.html.

and over a 100-year period that includes 50 years of injection and 50 years of post-injection monitoring.

In the ideal situation, a scenario is expected to look something like the shaded area in Figure 2, which shows the expected risk of leakage of $CO_2$ from geologic storage over a project's lifetime. It illustrates the expectation that at properly-sited, operated and closed CCS projects, the risk starts at zero, rises while early injection increases pressures in the storage formation, flattens during routine operation and then falls when injection ceases. The risk then further decreases over time to nearly zero as the injected $CO_2$ dissipates into the geologic formation and various geologic trapping mechanisms have more effect.

In reality, this is just one possible outcome. A project may face unforeseen site conditions, such as an undetected old well or fault; operator error; or some other factor could come into play. Mitigation may be prompt or it may be delayed. The population characteristics around the site may change over time. The output from a single scenario is of one possible outcome but, if it is run multiple times with different possible assumptions, the model will produce multiple outcomes drawing on many possible combinations of the underlying conditions. This random sampling of the range of possible outcomes serves as the basis for a statistical analysis of the likely outcomes.

### Step 5: Use Probabilistic Modeling to Explore the Range of Possible Costs

Monte Carlo simulation is a widely-used and well-accepted method for modeling uncertain financial outcomes. As discussed below, IEc constructed the model to use Monte Carlo simulation to generate, compile, and analyze an array of roughly 100,000 possible scenarios, a sample size that is large enough to generate confidence in the results. The model compiles the results from these scenario probability distributions of the cost of damages. These probability distributions illustrate the statistical range of possible outcomes from the modeled project.

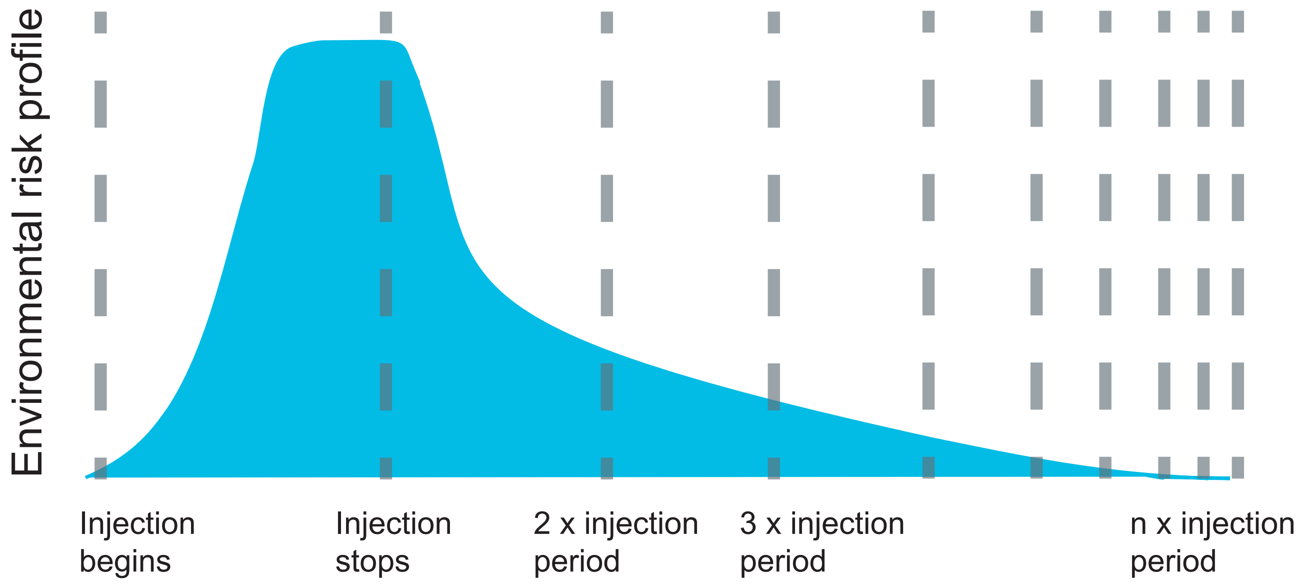


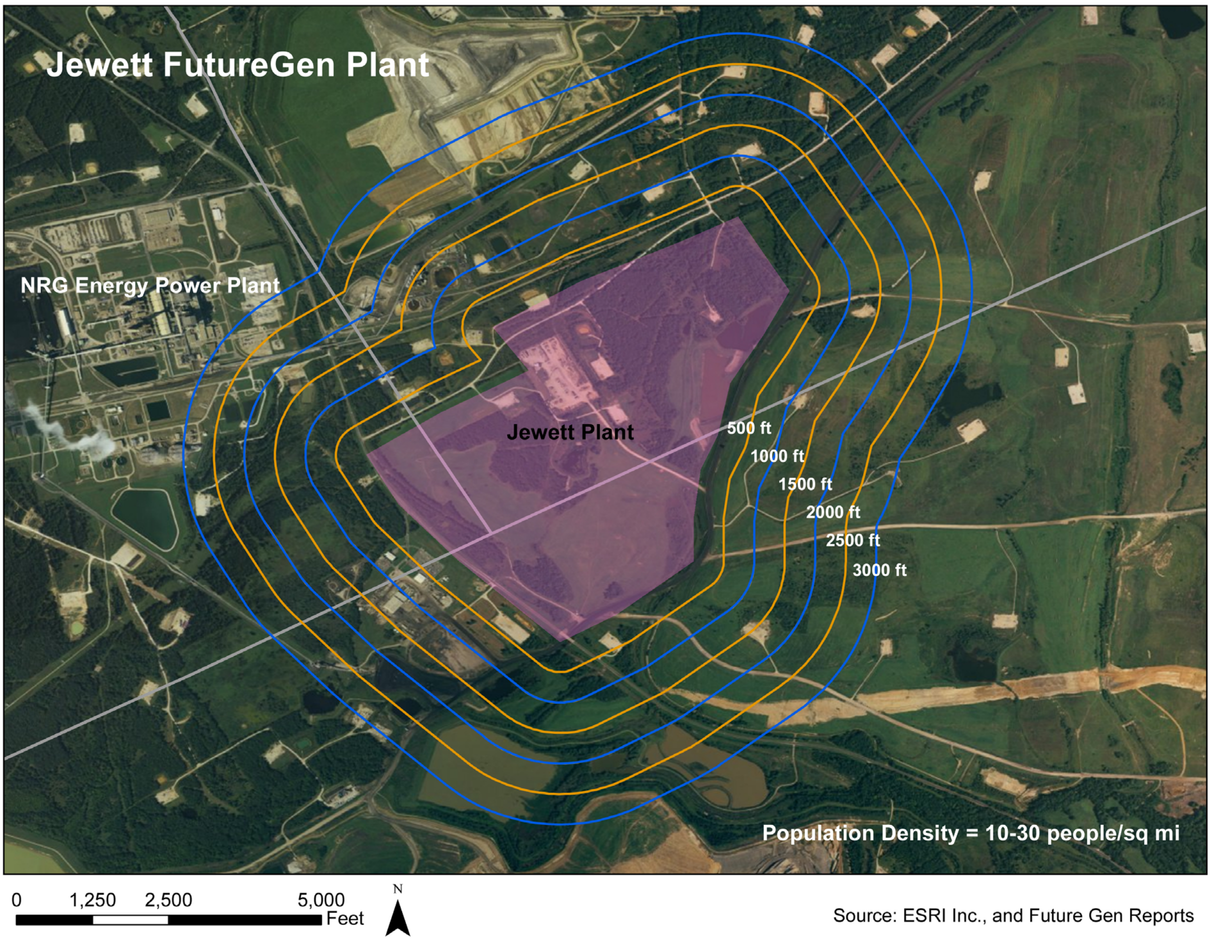

Figure 2: Hypothetical example of the variation of risk over time for geologic storage of $CO_2$. Source: Adapted from Sally Benson, Stanford University.

Estimates of distributions of financial damages were made for a proposed CCS project in Jewett, Texas in the United States. This project was one of several proposed as part of the US Department of Energy's FutureGen initiative. FutureGen is a public-private partnership that intended to build and operate an integrated CCS project in the US[4]. Announced in 2003, the original concept (FutureGen 1.0) established a competition to encourage entities to submit proposals for specific projects located at specific sites. This process was shared with the public through publicly available documents posted on the FutureGen website. The original set of submissions was narrowed to a group of four sites, one of which was the Jewett, Texas project.

Each of the four selected projects submitted a detailed Environmental Impact Volume (EIV) in order to continue in the competition. The EIVs were developed through a peer-reviewed process and provided detailed technical risk assessments for these specific locations. The EIVs were preliminary assessments based mostly on available data rather than new site characterization work (i.e., new seismic surveys, test wells). It was understood that once a final site was selected, additional site characterization work would be undertaken for project finalization and design. (Such additional site characterization was not expected in the published Jewett risk assessment given the stage of the decision process). Still, the publication of the four EIVs was a valuable resource in developing approaches for evaluating economic risk. IEc reviewed the four candidate sites and determined that they provided enough information to test the model and to develop insights from the results. The Jewett, Texas site was selected and the risk assessment in its EIV was used as the basis for the test.

### Project Description

The proposed Jewett project included a 275 Megawatt integrated gasification combined cycle (IGCC) power plant on a site of about 75 acres (30 hectares) located in a rural setting with a low population density.




Source: ESRI Inc., and Future Gen Reports

Figure 3: Overview of Jewett FutureGen site.

4 For a concise description of the current FutureGen project see the FutureGen Alliance website: http://www.futuregenalliance.org/.

Given the nature of the specific IGCC process, the plant would capture $CO_2$ and trace amounts of hydrogen sulfide ($H_2S$), an acid gas that also has health effects but would not be present in many CCS projects. This mix would be transported through a 59-mile (95-kilometer) pipeline to another rural setting where up to three wells were planned for injection. The area around the injection wells was primarily used as ranchland and the project had acquired the right to use 1550 acres (627 hectares) surrounding three potential injection wells. Figure 3 shows the layout of the Jewett project, including the capture plant, pipeline and injection sites for sequestration.

The site-specific characteristics were generally considered to provide a low-risk environment for a CCS demonstration in that the geologic formations included substantial reservoirs for injection and it appeared that there was a good and thick cap rock. Further it was located in a region that was sparsely populated with limited potential for biodiversity impacts.

### Making Estimates

The risk assessment for the Jewett site made quantitative estimates of the magnitude and probability of those risks deemed to have some potential for harm based on site characteristics and provided a qualitative discussion of those risks deemed not important at the site. This assessment was based primarily on information available at the time. Developing quantitative estimates for the remaining risks would have required additional advanced site characterization work. In order to apply the comprehensive model to the Jewett site, the study participants developed a "hybrid" case that included assumptions for the risks and/or variables which could not be quantified using data from the Jewett risk assessment. What follows is a brief description of how the data were included in or addressed through each of the steps of the model.

### Step 1. Selection of Relevant Risk Events

The risk assessment was reasonably thorough and evaluated several potential events and mechanisms at the Jewett site associated with capture, transport, and injection through which $CO_2$ or $H_2S$ could leak or be released and was the primary source relied upon to select relevant events. IEc included the release of $H_2S$ in the damage assessment modeling consistent with the risk assessment findings that releases of this substance at this site had the potential to cause human health and/or environmental impacts.

### Step 2. Characterize the Magnitude and Probability of Risk Events

For most of the identified events and mechanisms, the FutureGen risk assessment quantified the magnitude of potential releases and the probability of their occurrence based on site-specific information. Event probability estimates not included in the original EIV, such as yearly rates of pipeline accidents and failure of separation/compression equipment, were addressed through review of comparable, publicly-available data and discussion with industry experts. Event magnitude information was also missing for a few types of events (e.g., the amounts and durations of release of injected gas from the deep well to groundwater at the surface and from the deep well to the atmosphere).
The project sponsors consulted among themselves and with experts to develop specific assumptions for these variables for use in testing the model.

### Step 3. Evaluate the Potential Costs of Impacts

IEc considered technical literature and publicly-available databases to tailor their cost curves to the Texas site. For example, they reviewed Texas case law and other databases to determine certain costs related to human health damages. Potential groundwater damages were dependent in part on the background mineral content of the rock formations in the region, which was not included in the risk assessment. In that case, the project sponsors consulted among themselves and with experts to develop an average mineral content variable for use in testing the model.

### Steps 4 and 5. Evaluate the Site Using Probabilistic Simulation

IEc conducted 100,000 model runs for the Jewett project. This large number of samples was used to help ensure that the resulting distribution of the probability of financial damages appropriately captured the effects of even low probability events.

## RESULTS

The median value of damages at this site from the 100,000 model runs are estimated to be US$7.3 million, as indicated in Figure 4. Total damages estimates for 95 per cent of all model runs were below US$16.9 million. These estimates translate into approximately US$0.15 and US$0.34 per tonne of the total of 50 million tonnes of $CO_2$ expected to be sequestered at the Jewett Site. These estimates value all potential adverse events over the 100 years and are expressed in 2010 dollars.

The distribution of the damages shown in Figure 4 is for $CO_2$ only since that would probably be similar to most CCS projects. The distribution values were about 10-15 per cent higher when potential leakages of $H_2S$ were included. $H_2S$ releases are the primary driver of human health effects in this case.

The model shows that more than 95 per cent of the estimated damages at this site are due to potential releases from existing oil and gas wells at this site – risks that could be mitigated through well completion work or that would be avoided at projects that are not located in oil and gas production areas.

Risks associated with other types of events – at the sequestration site, at the capture plant, or from the pipeline – are negligible or very low.

This result serves as a preliminary estimate but some remaining uncertainty regarding carbon prices and impacts have not fully assessed at the site. Such uncertainty could be reduced through further site characterization work.

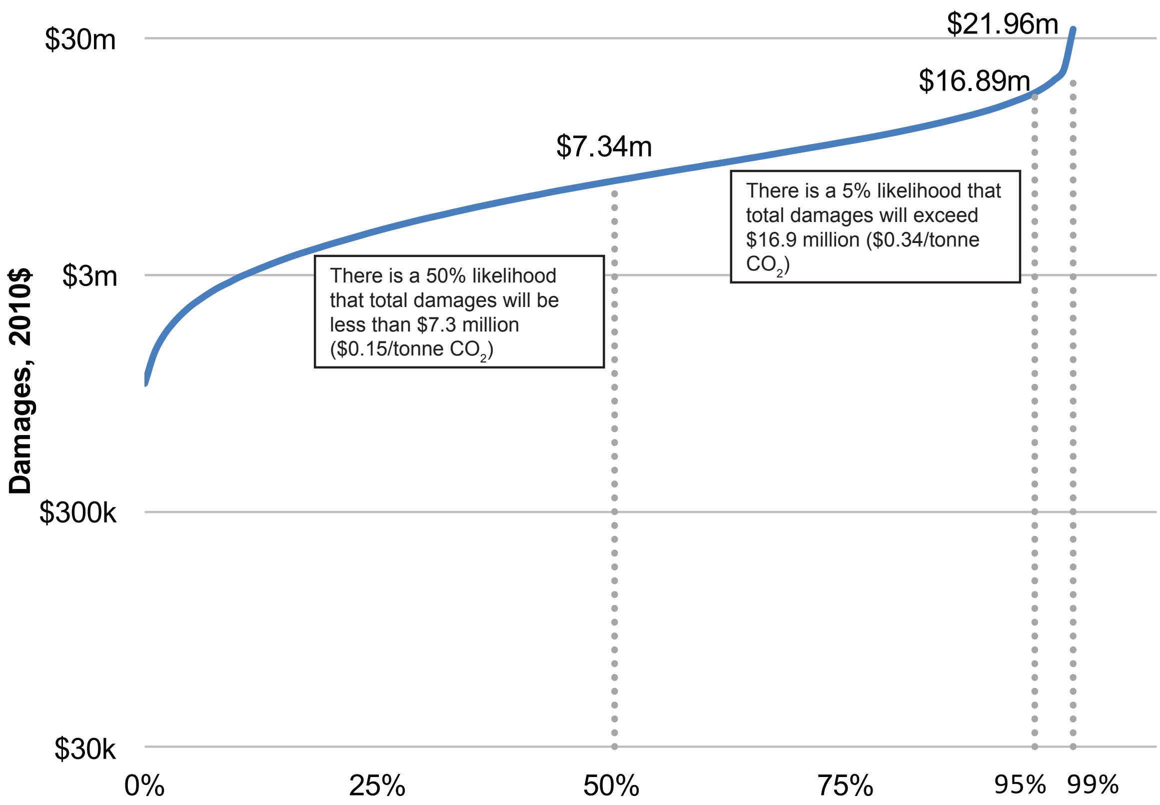



Figure 4: Estimated Jewett Project Damage Distribution for $CO_2$ capture, transport and storage. Source: Industrial Economics, Incorporated, "Valuation of Risks Arising from a Model, Commercial-scale CCS Project Site," Cambridge, MA, June 2012.

# CONCLUSIONS

This study demonstrates that the financial risks associated with CCS projects can be quantified by standard analytical techniques. This challenges the widespread misperception that the costs associated with the risks of CCS cannot be quantified. It further shows how uncertainty can be explicitly taken into account.

This study demonstrates that well-sited and well-operated CCS projects can be expected to result in a relatively small potential financial risk for damages to human health and the environment compared to both the planned project costs and the benefits of such projects. Choice of the site is critical. Site characteristics – both the geologic factors that affect risk and the potential exposure of humans and the environment – are major determinants of risks. Although the results are based on a single early-stage project using generalized data, they give insight into the likely range of damage costs that can be expected at well-selected and operated projects.

Importantly, this flexible approach can be applied to projects at different stages of development. Early in project development, when detailed site-specific information is limited, general data from multiple sources can be used for site screening and selection. As site-specific, more-detailed and accurate data is gathered, this better data can be used to improve risk estimates, finalize site selection and design the project to minimize risks. As the project is implemented, the approach can be used to improve the safety of operations and avoid potential problems before they arise.

The application of the approach used in this study can help developers of CCS projects better site and design their projects to mitigate risk and confidently make investment decision. This information can be used by regulators and project developers to inform regulatory and permitting decisions and to establish regulatory timeframes and financial assurance mechanisms. The financial community can use this information to better evaluate project investments. Perhaps most importantly, this information can be shared with the public to build confidence in projects.