A MULTI-CRITERIA DECISION ANALYSIS AND RISK ASSESSMENT MODEL FOR CARBON CAPTURE AND STORAGE

by

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ABSTRACT

Currently several disparate and incomplete approaches are being used to analyse and make decisions on the complex methodology of carbon capture and storage (CCS). A literature review revealed that, as CCS is a new and complex technology, there is no agreed-upon thorough assessment method for high-level CCS decisions. Therefore, a risk model addressing these weaknesses was created for assessing complex CCS decisions using a multi-criteria decision analysis approach (MCDA). The model is aimed at transparently and comprehensively assessing a wide variety of heterogeneous CCS criteria to provide insights into and to aid decision makers in making CCS-specific decisions.

The risk model includes a variety of tools to assess heterogeneous CCS criteria from the environmental, social, economic and engineering fields. The model uses decision trees, sensitivity analysis and Monte Carlo simulation in combination with utility curves and decision makers' weights to assess decisions based on data and situational uncertainties. Elements in the model have been used elsewhere but are combined here in a novel way to address CCS decisions.

Three case studies were developed to run the model in scenarios using expert opinion, project-specific data, literature reviews, and engineering reports from Alberta, Saskatchewan and Europe. In collaboration with *Alberta Innovates Technology Futures*, a pilot study was conducted with CCS experts in Alberta to assess how they would rank the importance of CCS criteria to a project selection decision. The MCDA model was run using experts' criteria weights to determine how CCS projects were ranked by different experts.

The model was well received by the CCS experts who believed that it could be adapted and commercialized to meet many CCS decision problems. The survey revealed a wide range in experts' understanding of CCS criteria. Experts also placed more emphasis on criteria from within their field of expertise, although economic criteria dominated weights overall. The results highlight the benefit of a model that clearly demonstrates the tradeoffs between projects under uncertain conditions. The survey results also revealed how simple decision analyses can be improved by including more transparent methods, interdisciplinary criteria and sensitivity analysis to produce more comprehensive assessments.

LIST OF ABBREVIATIONS USED

AHP	Analytical hierarchy process
AITF	Alberta Innovates: Technology Futures
AP	Acidification potential
BAU	Business as usual
C_2H_4	Ethylene
CBA	Cost benefit analysis
CCS	Carbon capture and storage
CDM	Clean development mechanism
CFCs	Chloroflourocarbons
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2CRC	Cooperative Research Centre for Greenhouse Gas Technologies
COE	Cost of electricity
CSLF	Carbon sequestration leadership forum
ct	Cents, one hundredth of a dollar
DSS	Decision support systems
ECMB	Enhanced coal-bed methane
ELECTRE	Elimination and choice translating reality
ENGO	Environmental non-governmental organization
EOR	Enhanced oil recovery
EP	Eutrophication potential
ETP	Eco-toxicity potential
EU	European Union

FEED	Front end engineering and design
GDP	Gross domestic product
GHG	Greenhouse gas
GP	Goal programming
GT	Gigatonne
GWP	Global warming potential
H_2	Hydrogen
H_2S	Hydrogen sulphide
HCFC	Hydrochlorofluorocarbons
HTP	Human toxicity potential
IEA	International Energy Association
IEAGHG	IEA Greenhouse Gas Program
IGCC	Integrated gasification combined cycle
IPAC-CO_2	International Performance Assessment Centre for geologic storage of CO_2
IPCC	Intergovernmental Panel on Climate Change
ISO	International Standardization Organization
kWh	Kilowatt hour
LCA	Life cycle assessment
LCI	Life cycle inventory
MACC	Marginal abatement cost curve
MAUT	Multi-attribute utility theory
MAVT	Multi-attribute value theory
MCDA	Multi-criteria decision analysis
MCDM	Multi-criteria decision making
MEA	Monoethanolamine

MT	Megatonne
MW	Megawatt
NGO	Non-governmental organization
NIMBY	Not in my back yard
NO_x	Nitrous oxide
O_2	Oxygen
OOIP	Original oil in place
OPEX	Operating costs/expenses
PFC	Perfluorocarbons
PFM	Preference function modeling
PO_4^{3-}	Phosphate
POCP	Photochemical ozone creation potential
PPB	Parts per billion
PPM	Parts per million
PROMETHEE	Preference ranking organizational method for enrichment evaluation
RES	Renewable energy source
SMART	Simple multi-attribute rating technique
SO_2	Sulphur dioxide
STEM	Step method
SF_6	Sulphur hexafluoride
TOPSIS	Technique for order preference by similarity to ideal situations
UNFCCC	United Nations Framework Convention on Climate Change
VOC	Volatile organic compounds
WCSB	Western Canadian sedimentary basin
YOLL	Years of life lost

GLOSSARY

Acidification Potential (AP) (gSO_2 -equivalent/kWh):

Acidification is the process of reducing the pH of a substance, in this context through the release of SO_2 emissions from burning fossil fuels at a power generation plant (Penht and Henkel, 2009).

Black Box Decision Analysis:

A black box decision analysis is a model in which some, or all of the model is not understood by the decision maker. This is the opposite of a transparent and user friendly model. Technical parameters and complex math should either be avoided or well explained to users (Figueira *et al.,* 2005).

Capital Cost ($):

Capital cost includes all the costs involved in developing the project and constructing all the necessary components of the CCS plant including capture, transport, injection, monitoring and decommissioning.

Capture Cost ($):

Capture cost refers to the operating costs for capturing CO_2 and separating the gas from the flue gas of a fossil-fuelled power plant.

Carbon Dioxide (CO_2):

Carbon dioxide is the most important greenhouse gas causing between 9 and 26% of the overall greenhouse effect and on the order of 75% of anthropogenic portion (Kielh and Trenberth, 1997). CO_2 is by far the most abundant anthropogenic gas, which accounts for its large impact on climate change despite its low GWP.

CO_2 Capture Efficiency (%):

CO_2 capture efficiency refers to the percentage of CO_2 gas that is captured from the flue gas of a power plant. The portion that is not captured is released into the atmosphere. A higher efficiency is thus preferred for CCS.

CO_2 Storage:

The three major types of storage mediums being researched include oil and gas reservoirs, deep saline formations and unmineable coal-beds. Each storage method involves injecting CO_2 into dense rock formations up to several kilometres below Earth's surface. Suitable storage sites have been identified in both on and offshore locations (IPCC, 2005).

CO_2 Transportation:

The main types of transportation include, truck, boat and pipeline. For quantities that are very small, trucks may be the least expensive option. For distances that are up to 1,000 kilometres and those that involve large quantities, pipelines are the preferred option. For overseas transportation, ships are the most economically attractive option (IPCC, 2005).

Cost Benefit Analysis (CBA):

Cost benefit analysis as a concept is one of the most widely used economic methods for decision making. It is aimed at maximizing economic benefits while minimizing costs (Pohekar and Ramachandran, 2004). It includes methods that characterize the social consequences of decisions based exclusively on monetary values (Munier, 2004). All attributes of a project are translated into money values (Cavallaro, 2009).

Cost of Electricity (COE) ($/kWh):

Cost of electricity is the price that consumers pay for each kWh, including all subsidies and extra costs of adding CCS to a fossil-fuelled power plant.

Energy Penalty:

The process of capturing, compressing and transporting CO_2 from a power plant requires a significant amount of energy and is referred to as an energy penalty. Approximately 10-40% additional energy is required to produce electricity from a CCS power plant as compared with a similar plant without CCS depending on the conditions and the technology used (IPCC, 2005).

Enhanced Oil Recovery (EOR):

EOR involves injecting CO_2 into oil and gas wells to re-pressurize the reservoirs and produce more oil and gas. This process can help produce incremental oil above what is produced during primary production. When CO_2 is injected into depleted oil and gas reservoirs, it dissolves in the oil resulting in swelling and reduction in viscosity and re-pressurizes the reservoir (Meadowcroft and Langhelle, 2010). Approximately 30 Mt of natural CO_2 is injected into oil fields (mostly in Texas) annually with small projects throughout the world. Currently there are over 50 individual sites, some of which have been in use since the 1970s (IPCC, 2005).

Eutrophication Potential (EP) (PO_4^{3-}-equivalent/kWh):

Eutrophication is caused by a series of chemicals such as NO_x, SO_2, NH_3 and PO_4^{3-} and refers to the excessive supply of nutrients to soil and water (Pehnt and Henkel, 2009). Due to the increased energy required when introducing CCS, the eutrophication potential can double when CCS is added to a post combustion coal plant. NH_3 is the main eutrophication contributor caused by the degradation of the MEA medium used in the CO_2 capture process.

Functional Unit:

A functional unit is a quantified description of the performance of the product systems, for use as a reference unit (Danish Ministry of the Environment, 2004). The functional unit is used in assessments to compare alternatives using the same units and scale.

Global Warming Potential (GWP) (gCO_2-equivalent/kWh):

Although CCS reduces the quantity of CO_2 emitted into the atmosphere, due to the energy penalty of CCS, extra construction material and imperfect capture technology; CO_2 is still emitted into the atmosphere. GWP is used as a measure of an activity's impact on climate change. The GWPs used by the IPCC are a function of radiative forcing and atmospheric lifespan. All GWPs are in relation to carbon dioxide which has a default rating of 1.

Human Toxicity Potential (HTP) (years of life lost):

Human toxicity is mostly a function of flue gas emissions from fossil-fuelled power plants comprising HF, NO_x, SO_2, HCl and particulate matter (Koornneef *et al.,* 2008), all of which have a negative impact on human health.

Intergovernmental Panel on Climate Change (IPCC):

The IPCC is an international organization established in 1988 by the world meteorological organization and the United Nations environment program. The IPCC provides scientific assessments of the risks of climate change caused by human activities.

Knowledge of CCS (constructed scale 0-1):

Awareness and understanding of CCS by the public.

Life Cycle Assessment (LCA):

LCA is a method for measuring all the inputs and outputs of a system or process over its entire lifespan from conception to disposal (and sometimes includes post disposal monitoring or remediation). LCA is often used in environmental projects and was first comprehensively used for assessing CCS by Viebahn *et al.,* in 2007 (Pehnt and Henkel, 2009). LCA methodologies have been formalized by the International Organization for Standardization (ISO) in their 14040 series of standards.

Multi-Criteria Decision Analysis (MCDA):

Multi-criteria decision making (or multi-criteria decision analysis) has become more popular when dealing with complex problems and is starting to be used in assessing energy options (Wang *et al*., 2009). The process is similar to that in LCAs in that it assesses many criteria. It differs from LCAs however, in that emphasis is put on amalgamating and weighting the different criteria in order to give a more comprehensive conclusion or recommendation. MCDA can input data from LCAs and CBAs and then applies decision maker's weightings to determine which project is best overall.

Operating Cost (\$):

Operating cost refers to the ongoing maintenance and costs associated with keeping a CCS plant working.

Oxyfuel CO_2 capture:

Oxyfuel is a less mature technology than either post or pre-combustion and involves injecting a high purity oxygen stream into the fossil fuel combustion phase of CCS. The major costs with the oxyfuel capture method are from separating oxygen from air, but like pre-combustion, the process produces a very pure CO_2 (almost 100%) gas stream, lowering costs in the separation phase.

Payback Period:

A common measure used in economic analysis is the payback period, which refers to the amount of time required for an investment to give a full return on capital costs (Park *et al.,* 2000).

Perceived Impact on Climate Change (constructed scale 0-1):

Perceived impact of CCS on climate change relative to other climate change mitigation options and is based on surveys of public opinion.

Perceived Impact on Health (constructed scale 0-1):

Public perception of the positive or negative impacts of CCS on human health.

Perceived Impact on Other Technologies (constructed scale 0-1):

Perceived impact of CCS on the development of other climate change mitigation technologies. One common concern regarding CCS is that pursuing the technology will reduce the effort and funding to sustainable climate change mitigation actions such as renewable energy projects.

Photochemical Ozone Creation Potential (POCP) (g C_2H_4-equivalent/kWh):

POCP, also referred to as 'summer smog' is the creation of near-ground ozone through the combination of sunlight, nitrogen and volatile organic compounds (VOCs). VOCs and nitrogen oxides are produced in the combustion of fossil fuels. POCP negatively impacts breathing and inhibits plant functions.

Post-Combustion CO_2 Capture:

Post-combustion CCS technology is the most developed CO_2 capture technology and already is in use in several locations worldwide. The capturing and separation portion of CCS has been in use for several decades in the natural gas processing industry (IPCC, 2005). Post-combustion CO_2 capture refers to collecting CO_2 gas from the flue gas after the fuel has been burned. The capturing therefore takes place in the flue gases and is similar to other processes involving 'scrubbing' pollutants out of the smokestack such as those for removing SO_x and NO_x.

Pre-Combustion CO_2 Capture:

Pre-combustion CO_2 capture technologies have also been in use in some form for many years, mostly in fertilizer manufacturing and hydrogen production (IPCC, 2005). This method of capturing CO_2 is currently more complex and expensive than post-combustion CO_2 capture. The gas stream however has a much higher concentration of CO_2 and higher pressures making the separation less costly and roughly comparable overall to post-combustion CO_2 CCS. The pre-combustion process involves partially oxidizing the fossil fuel which reacts with steam to form CO_2 and H_2. The hydrogen is then used directly as a fuel combustion source. The CO_2 concentrations from the emissions are much higher than those in post-combustion capture and are typically in the range of 15-60% (Rackley, 2010).

Project (system) Boundary:

The project boundary is the interface between a system being studied and the environment that is not included in the study. Several factors determine the system boundaries, including the intended application of the study, the assumptions made, cut-off criteria, data and cost constraints, and the intended audience (ISO 14040, 2006).

Public Perception (constructed scale 0-1):

Overall opinion of the CCS project by the public.

Radiative Forcing:

Radiative forcing is a measure of the influence a factor has in altering the balance of incoming and outgoing energy in the Earth-atmosphere system and is an index of the importance of the factor as a potential climate change mechanism. Radiative forcing values represent changes relative to preindustrial conditions set at the year 1750 and are expressed in watts per square metre (W/m^2) (IPCC, 2007).

Risk Analysis:

The term risk is often referred to in terms of the likelihood of events combined with their associated consequences (ISO, 2009b). Risk has also been defined as a "state of uncertainty where some of the possibilities involve a loss" (Hubbard, 2009). Risk analysis is a method for determining and assessing this combination of a negative consequence and its probability of occurrence.

Storage Cost ($):

Storage cost includes all aspects of injecting and monitoring CO_2 into a geological reservoir.

Storage Potential (Mt of stored CO_2):

Storage potential refers to the total reservoir capacity for storing CO_2 (usually in a geologic medium.

Supercritical fluid

A supercritical fluid refers to any substance with temperatures and pressures that enable the substance to simultaneously have properties of solids, liquids and gases. In the CCS context this enables CO_2 to be very dense and to occupy very small pore spaces in geological reservoirs for storage.

Threshold:

Criteria are evaluated based upon their numerical or nominal values in order to create a score. A threshold is a point beyond which the score of a criterion becomes unacceptable.

Transport Cost ($):

Transport cost includes the costs of compressing CO_2 and transporting the supercritical fluid to the storage site via pipeline, truck or ship.

Utility:

Utility is used as a measure of the usefulness of an item, or of how much service it is to a person. It can also be used to represent preferences between different choices. When comparing different alternatives, it is important to use the same scale for all criteria, such as “utility units” (Clemen, 1996). In order to compare heterogeneous criteria, utility curves are often used.

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CHAPTER 1
INTRODUCTION

1.1 CARBON CAPTURE AND STORAGE DECISION MODELING

Climate change is one of the most complex challenges facing humankind today (Patz *et al.,* 2005; DSF, 2009; Major economies forum, 2009; Rackley, 2010; Chan, nd). The largest contributor to anthropogenic climate change is the emission of carbon dioxide (CO_2), due in large part to society's reliance on fossil-fuelled power plants to produce electricity. There are, however, mitigation techniques and technologies that can reduce CO_2 emissions such as energy conservation, greater reliance on renewable energy and or nuclear power, and carbon capture and storage (CCS). A suite of actions will be needed to adequately limit anthropogenic climate change (IPCC, 2005). The CCS process captures, transports, and stores CO_2 from fossil-fuelled power plants in deep permanent geological reservoirs (IPCC, 2005). As CCS is a large-scale and new technology, there are significant uncertainties related to its costs, impacts and implementation. For instance, the public is largely ignorant of CCS and have many misconceptions of the technology (Huijts *et al.,* 2007; Ashworth *et al.,* 2009).

Whereas individual components of CCS have been in use for several decades for various purposes (Havercroft *et al.,* 2011), integrating all three aspects of CCS has only recently been explored as an effective climate change mitigation method. CO_2 capture has long been used to remove impurities in the petrochemical industry and for carbonating beverages. CO_2 injection into geological reservoirs is used to re-pressurize and change the reservoir conditions in order to extract more oil from reservoirs. Transporting CO_2 in pipelines to deliver CO_2 from both natural and anthropogenic sources to refineries and oil reservoirs is also widespread. However, very few large-scale CCS projects integrating all three stages have been developed to date (IPCC, 2005 and MIT, nd).

CCS projects are to be integrated with fossil-fuelled power plants which necessitates a large scale, resulting in high costs. Some characteristics of implementing CCS attributes have limited the development of the technology. Its long lifecycle and potentially wide geographical impact have required the development of new regulations about ownership and liability of CO_2 and CCS (Government of Alberta, 2010). The uncertain capital and operating costs and potential impacts on the environment and human health have also resulted in delayed and cancelled CCS projects due in part to public opposition (Terwel *et al.,* 2012).

Research is needed to understand how best to implement CCS and to avoid the problems which have delayed the development of CCS to date. Decision analysis is a formal method of assessing choices and providing recommendations for these choices. Most CCS studies have focused primarily on specific aspects of CCS (economic, social, engineering and environmental) in isolation of one another. These CCS assessment studies also tend to use methods that limit cross-disciplinary research. Current research studies can generally be grouped into life cycle assessments (LCAs) for environmentally-focused investigations, cost benefit analysis (CBA) for economic studies, and social surveys for public perception of CCS. The lack of interdisciplinarity between assessment methods has hindered comprehensive comparisons of CCS projects and limited the broader understanding of the field (IEA, 2010).

Multi-criteria decision analysis (MCDA) is a method that is increasingly used to assess complex energy problems such as CCS (Wang *et al*., 2009). The method involves incorporating data from primary sources, or those produced from studies such as LCAs, CBAs and social surveys in order to input it into a decision analysis framework. Decision-makers (DMs) amalgamate the data and assign relative weights based on their perceived importance to the decision. The data-weighting process produces a DM-specific decision analysis that can be tailored to meet the needs of assessment. MCDAs also allow for qualitative and quantitative data to be compared on compatible scales (Cavallaro, 2009). The process enables complex decisions to be assessed more holistically. Furthermore, since the future costs, benefits and impacts of implementing a CCS project are indeterminate, this uncertainty must be incorporated into the decision analysis using a risk model.

The focus of this thesis is to create a risk assessment model for CCS decisions using a MCDA approach. While individual elements of the model have been used elsewhere, these elements have been brought together in a novel way here for decision modeling of CCS-specific problems.

1.1.1 Objectives

The main objective of this thesis is to develop a risk assessment model to facilitate CCS decisions that incorporate social, economic, engineering and environmental criteria using a MCDA approach. To develop a decision assessment model many steps had to be completed. A literature review of recent CCS studies was conducted to identify the major CCS risk factors (criteria), to compare assessment methods currently used, and to collect data on the relevant criteria. A survey of CCS experts was also conducted to elicit further risk factors. Probability distributions of criteria values were developed based on the literature review and also with CCS experts' opinions. Representative CCS project scenarios were created using this information to compare tradeoffs. DMs are faced with many choices for implementing CCS projects that necessitate tradeoffs. These can include decisions such as selecting the type of CO_2 capture technology, location of CO_2 storage, level of public and stakeholder engagement, level of environmental and health monitoring, as well as developing strategies for reducing and mitigating CO_2 leakage risks, while balancing the need to limit capital and operating costs.

1.1.2 Risk Model Development Methodology and Demonstration

To enhance and integrate MCDA methods into the risk model to address CCS-specific problems, many decision assessment tools were implemented. Only tools that would provide a direct benefit to a CCS assessment model were included to avoid complicating the model and reducing its usability. The MCDA CCS risk model[1] includes uncertainty in criteria data and DM preferences, through using Monte Carlo simulation, criteria weights, utility functions and sensitivity analyses. The risk model also enables the inclusion of heterogeneous units for diverse criteria, and both quantitative and qualitative data that span economic, social, engineering and environmental aspects of CCS. The risk model's flexibility allows for a wide range of decisions to be assessed by working through a series of questions and steps. DMs can individualize the model to suit their specific needs and preferences. The risk model is therefore not prescriptive in its recommendations but rather serves DMs to better understand the tradeoffs between alternatives. The emphasis on transparency allows the model to avoid "black box" problems where DMs do not understand the model and therefore do not trust the results.

To demonstrate the CCS risk model, three representative CCS projects were developed. The projects were created using front end engineering design (FEED) studies, peer-reviewed literature data, project-specific data and expert opinion. A survey of CCS experts in Alberta was conducted to elicit their opinions of the relative importance of CCS criteria to project selection. The CCS experts were categorized by their background (focus-area of employment or research) and expertise into governmental, environmental, research and industry groups. Both the individual and category responses were used as inputs into the model case study to represent CCS DMs' opinions. Monte Carlo simulations were performed using the uncertainties in criteria values and expert opinion responses. A one-way sensitivity analysis using the case studies determined whether the uncertainties in criteria data and expert criteria weights (relative preferences of importance of criteria) could have a significant impact on the selection of projects.

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[1] The MCDA CCS risk model developed for this thesis is hereafter referred to as the 'risk model'.

A study of possible extreme negative events was created using data from the literature to assess the potential causes of CCS project cancellations worldwide. The study assessed the uncertainty in project selection and was compared with simple tools and assessment methods. Using these risk model elements, a DM is able to more comprehensively assess alternatives.

1.1.3 Chapter Outlines

The thesis includes seven Chapters and three appendices. Chapters 4, 5 and 6 represent key findings and have been submitted for publication. These Chapters therefore are formatted specifically for publication and contain their own abstracts, conclusions and references. A full list of references is provided following Chapter 7.

Chapter 1 is an introduction to CCS and decision analysis and outlines the objectives of the thesis. It provides context to the need for CCS as a climate change mitigation strategy, recent decision analysis methods for assessing CCS and outlines how the CCS risk model builds upon other methods.

This thesis combines the field of decision analysis with the emerging technology of CCS. There are therefore two literature review chapters, with Chapter 2 providing a context for CCS and Chapter 3 describing various methods that have been used to assess complex decisions that arise from technologies such as CCS. Subsequent chapters describe how a risk model using an MCDA approach may be used to assist with CCS decisions.

Chapter 2 reviews the scientific basis of climate change, with a description of the anthropogenic causes and sources of greenhouse gases, specifically CO_2. The need for CCS as a climate change mitigation strategy is then explained and how it can contribute to current emission reduction strategies using existing technology. A description is given of the different stages of CCS (CO_2 capture, transport and geological storage) as well as an outline of the different types of CCS technologies currently being used and those in development. A history of CCS assessment research follows with an explanation of the wide variety of CCS impacts including their associated risks, with an emphasis on CO_2 leakage from geological storage reservoirs. Chapter 2 concludes with a summary of existing and proposed CCS projects, and legal and regulatory obstacles that hinder the widespread development of CCS.

Chapter 3 provides an overview of decision analysis, as well as its evolution towards more systematic and complex methods. The most common decision analysis methods applied to related areas (life cycle assessments, energy modelling, cost benefit analysis, decision trees) are described. MCDA is presented as a comprehensive alternative to other common decision analysis applications. Other aspects of decision analysis are described including utility, critical event analysis, thresholds and one-way sensitivity analysis. The benefits and drawbacks of each decision analysis method are described, including how elements of each method can be incorporated into complex energy decision making. Lastly, a case study is used to illustrate some of the MCDA methods used to address large-scale complex energy decisions.

Chapter 4, entitled "An interdisciplinary perspective on carbon capture and storage assessment methods" reviews the current state of decision analysis for CCS. A literature review determines the criteria that were most often included in recent CCS assessments and reviews articles spanning economic, environmental, engineering and social analyses. The types of criteria used for assessing CCS are examined, and the interdisciplinarity of the articles is discussed as a key driver behind the need for a holistic model. The most commonly used criteria in each discipline form the basis for the subsequent comprehensive CCS risk model design and case studies. This chapter acts as a bridge, using information from Chapters 2 and 3 to influence both the choice of criteria and the methods used in the risk model employed in Chapters 5 and 6. It was submitted to the Journal of Industrial Ecology in June 2012 and is currently under review.

Chapter 5 describes in detail the development of the risk assessment model used in this thesis based on a MCDA approach. A simple CCS example is provided to demonstrate the model. The model uses elements of decision analyses that are employed alone in other models elsewhere. The model incorporates these elements in a novel way to comprehensively address CCS-specific decisions. The model is descriptive and informative rather than prescriptive, and therefore provides no universal optimal choice. By incorporating DMs' preferences and opinions into the assessment model, the results are individualized to meet the DMs' specific requirements. A "black box" approach is avoided by transparently and visually displaying statistical information about alternatives and their possible outcomes. The methodology incorporates uncertainty, heterogeneous criteria, utility curves, decision trees, sensitivity analysis and Monte Carlo simulation into the risk model in order to achieve the abovementioned outcomes. Chapter 5 was submitted to the Journal of Risk Assessment in October 2012.

Chapter 6 presents three CCS case studies developed for the risk assessment model. The CCS case studies were developed using front end engineering reports, peer-reviewed literature data, project-specific data and expert opinion in order to demonstrate the model. CCS experts in Alberta from industry, government, environmental non-governmental organizations and research organizations were interviewed about the model and their opinions on the CCS criteria used therein. They were asked to rate the relative importance of each criterion for making CCS decisions using the risk assessment model. Recommendations for improvements in the model for future assessments were also recorded. Chapter 6 was submitted to the Journal of Greenhouse Gas Control in November 2012.

Chapter 7 summarizes the main results and makes recommendations for future research. Although the CCS case studies outlined in Chapter 6 include only a limited number of CCS experts' opinions, and was confined primarily to Alberta whose residents already have a high-level of knowledge of CCS (IPAC-CO_2, 2011), the results nonetheless provide valuable perspectives into the subject. Finally, the model has face validity[2] according to experts' feedback. However, it should be acknowledged that CCS is still a novel technology and there is

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[2] Face validity refers to the ability of a model to properly test or assess the property that it claims to test (Turner, 1979).

no long term historical basis by which to evaluate the effectiveness of CCS decisions made using the tool.

Three appendices conclude the thesis. The first appendix elaborates on climate change science, and CCS technologies, risks and developments. Appendix 2 expands upon decision analysis methods and concepts discussed in previous chapters. Appendix 3 provides the details of the study design used in Chapters 5 and 6 and a detailed description of all the criteria used throughout the thesis.

CHAPTER 2
CARBON CAPTURE AND STORAGE

2.1 CLIMATE CHANGE

Climate change is considered by many to be the most serious threat facing the world (Patz *et al.,* 2005; DSF, 2009). Approximately 430Gt of carbon has been released into the atmosphere due to human actions over the past two centuries, increasing the atmospheric concentrations from 280ppm to 396ppm (Rackley, 2010). According to the Intergovernmental Panel on Climate Change (IPCC), CO_2 and other natural and anthropogenic forces have increased the global average surface temperature by $0.74 \pm 0.18^{\circ}C$ over the twentieth century (IPCC, 2007). Climate change models show that the observed global temperature increase can only be explained by anthropogenic causes (see Figure 1). Climate change is caused by many factors, of which the greenhouse effect is the most dominant (see Section 2.1.1). In recent years awareness of the seriousness of anthropogenic climate change, as well as an understanding of the scale of the problem, has led to increased research into climate change mitigation options (Leiserowitz, 2007).

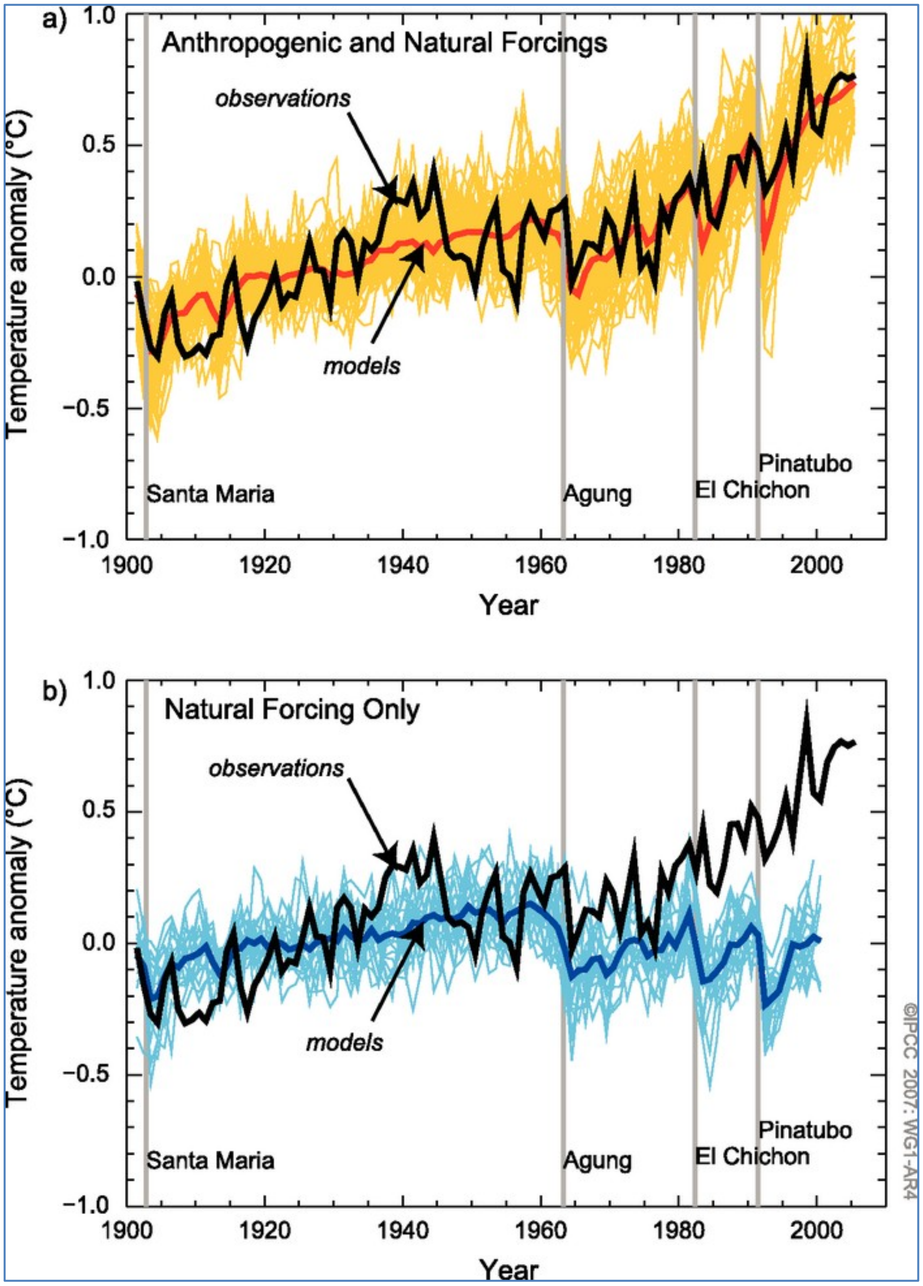

Figure 1 Global mean surface temperature trends and anomalies in the 20th century. In both graphs the black line represents the observed temperatures showing the upward trend and comparing the charts shows that natural forcing alone cannot account for the temperature changes. The vertical gray lines show major volcanic events which cause global temperatures to decrease temporarily. The upper graph shows the modeled natural and anthropogenic forcing on global temperatures in red. The lower graph shows only the effect that natural forcing would have on global temperatures in blue (IPCC, 2007).

2.1.1 Greenhouse Effect

The greenhouse effect is based on the principle that sunlight can pass through transparent substances, but the heat given off by this light does not pass back through as easily (Le Treut, 2007). In 1861, John Tyndall showed that both CO_2 and water absorb thermal radiation, which could have been the cause of the variation in climate that geologists had already observed in the geological record (Le Treut, 2007). Through the twentieth century and into the twenty-first, the interdisciplinary field of carbon cycle science led to a greater understanding of the effect of greenhouse gases on our climate (Le Treut, 2007).

The global greenhouse effect is caused by molecules that absorb thermal radiation in the atmosphere, of which anthropogenic sources of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrochlorofluorocarbons (HCFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF_6) have the largest impact and are regulated under the Kyoto Protocol (UNFCCC, 1998). These compounds are collectively described as greenhouse gases (GHGs) (see Appendix 1A for more details on these GHGs with respect to their sources and impacts). In addition to these regulated gases, there are naturally occurring GHGs including water vapour and ozone. The absorption of thermal radiation by GHGs in the atmosphere creates an insulating layer wherein heat is trapped (see Figure 2), similar to that observed on cloudy nights and in greenhouses. GHGs have modified the energy balance of Earth by trapping more heat within the atmosphere and thereby raising global temperatures.

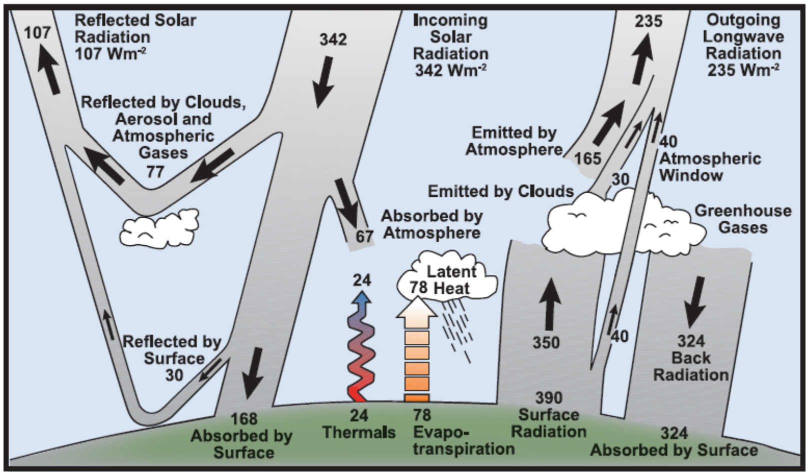

Figure 2 Estimate of the Earth's mean annual energy balance. Increases in greenhouse gases have resulted in an increase in thermal radiation towards Earth, causing global mean temperatures to rise (Le Treut, 2007)

The IPCC was established in 1988 by the World Meteorological Organization and the United Nations Environment Programme. The panel consists of hundreds of scientists worldwide with the objective of providing "decision-makers and others interested in climate change with an objective source of information about climate change" (IPCC, nd). Regarding anthropogenic climate change and CO_2 emissions, the IPCC has stated in their latest report that:

> Global atmospheric concentrations of carbon dioxide, methane and nitrous oxide have increased markedly as a result of human activities since 1750 and now far exceed pre-industrial values determined from ice cores spanning many thousands of years [see Figure 3]. The global increases in carbon dioxide concentration are due primarily to fossil fuel use and land use change… Most of the observed increase in global average temperatures since the mid-20th century is *very likely* due to the observed increase in anthropogenic greenhouse gas concentrations (IPCC, 2007 p36).

A significant and growing body of research has shown that climate change is occurring through the release of anthropogenic greenhouse gases amongst other anthropogenic and natural causes (IPCC, 2007).

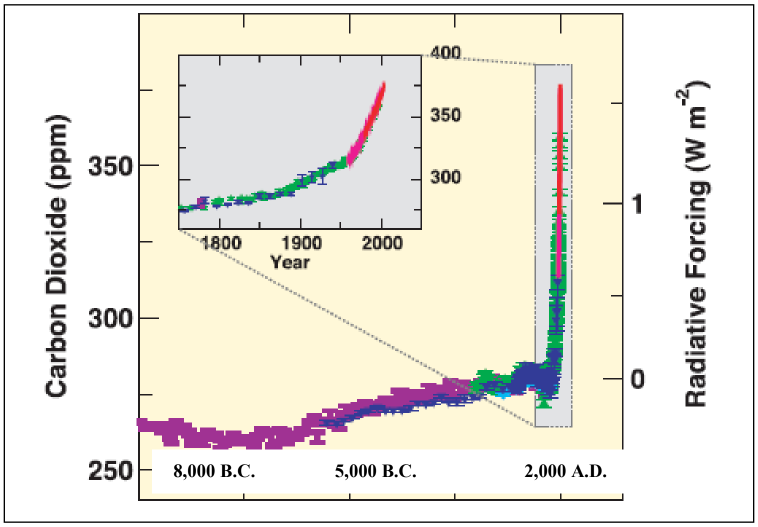

Figure 3 Atmospheric CO_2 concentrations for the past 10,000 years taken from ice cores showing a rapid increase over the past 200 years (Le Treut, 2007)

Global warming potential (GWP) is used as an index to compare different gases based on the relative impacts of their emissions on trapping radiated heat in the atmosphere, thus impacting climate systems (IPCC, 2001). The GWPs used by the IPCC are a function of radiative forcing[3] and atmospheric lifespan, which vary by type of GHG (see Appendix 1A for a description of GHGs, their GWPs and atmospheric lifespans). For a visual representation of the radiative forcing of natural and anthropogenic chemicals see Figure 4, which identifies CO_2 as the largest single influencing factor.

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[3] Radiative forcing is a measure of the influence a factor has in altering the balance of incoming and outgoing energy in the Earth-atmosphere system and is an index of the importance of the factor as a potential climate change mechanism. Radiative forcing values represent changes relative to pre-industrial conditions set at the year 1750, and are expressed in watts per square metre (W/m^2) (IPCC, 2007).

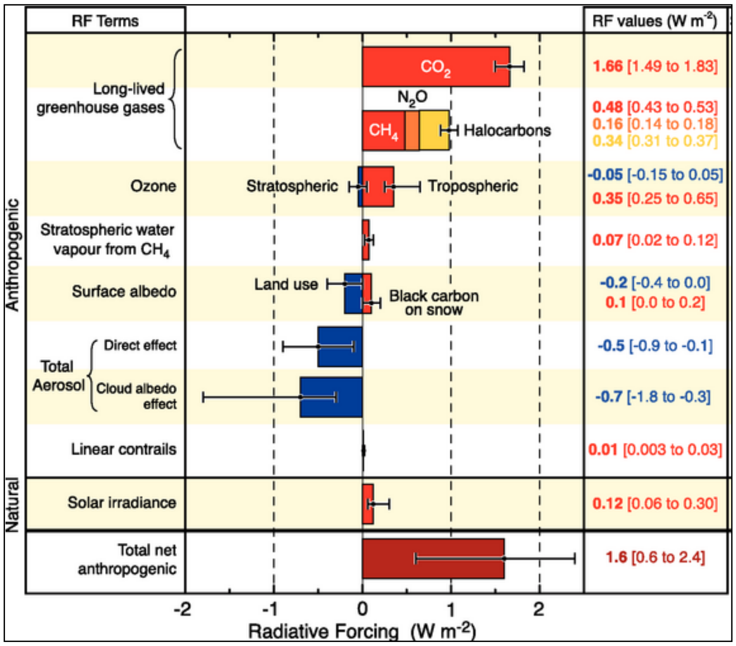

Figure 4 Radiative forcing (RF) estimates and ranges for different chemicals and mechanisms (IPCC, 2007)

2.1.2 Carbon Dioxide (CO_2)

Carbon dioxide, the most important anthropogenic greenhouse gas, causes between 9% and 26% of the overall greenhouse effect and approximately 75% of the anthropogenic portion (Kielh and Trenberth, 1997). CO_2 is by far the most abundant anthropogenic GHG, which accounts for its large impact on climate change, despite its relatively low GWP of 1. Natural and anthropogenic sources of CO_2 have different heavy isotope ratios, enabling scientists to roughly determine the level of atmospheric concentrations that are anthropogenic in origin (IPCC, 2007). Approximately 5% of all the geological carbon stored in the past several hundred million years through natural processes has been released by humans since 1750 (Rackley, 2010). Anthropogenic emissions have increased the atmospheric concentration of CO_2 over the past two centuries to April 2012 from 280ppm to 396ppm (NOAA, 2012). The impact on climate change has increased commensurately. The radiative forcing of climate caused by anthropogenic and natural processes is discussed further in Appendix 1A.

CO_2 is released into the atmosphere from a wide variety of sources, both natural (e.g. geochemical weathering from rocks and animal respiration) and anthropogenic, such as industrial processes, land use changes and the combustion of fossil fuels. The annual fluxes of natural and anthropogenic CO_2 between reservoirs are shown in Appendix 1A. Over the past 25 years the amount of CO_2 in the atmosphere has increased by between 3.2 and 4.1Gt of carbon per year, a relatively modest amount compared with natural carbon fluxes on the order of hundreds of Gts, but still sufficient to upset the balance. Approximately 55% of the anthropogenic CO_2 emitted does not add to atmospheric concentrations and is instead taken in by plants and absorbed into the oceans (IPCC, 2007). However, these storage reservoirs are in a dynamic equilibrium with the atmosphere, resulting in a decreasing capacity to continue storing CO_2, so we cannot rely on this phenomenon alone to solve climate change.

Fossil-fuelled combustion for electricity production, petrochemical refineries and cement manufacturing cause over 75% of anthropogenic CO_2 emissions, with most of the remaining 25% of emissions due to land use changes such as deforestation and its associated biomass burning (IPCC, 2007). The anthropogenic sources of CO_2 with emissions greater than 0.1 $MtCO_2$/yr are shown in Table 1. These sources represent approximately 60% of worldwide anthropogenic CO_2 emissions.

Table 1 Worldwide large CO_2 sources emitting greater than 0.1 $MtCO_2$/yr (adapted from IPCC, 2005)

Process	Number of sources	Cumulative emissions ($MtCO_2$/yr)
Fossil fuels		
Power	4,943	10,539
Cement production	1,175	932
Refineries	638	798
Iron and steel industry	269	646
Petrochemical industry	470	379
Oil and gas processing	Not available	50
Other sources	90	33
Biomass		
Bioethanol and bioenergy	303	91
Total	7,887	13,466

Electricity production worldwide is, on average, composed of coal-fuelled power plants (38%), followed by hydro (17.5%), natural gas (17.3%), nuclear (16.8%), oil (9%) and renewable sources such as wind and solar power (1.6%) (IPCC, 2005). The type of fuel chosen as an energy source is sector-specific; steel production uses primarily coal, whereas refining and chemical industries typically use oil and gas. Nevertheless, each country varies significantly in their primary energy source due in part due to their indigenous supplies; the U.S. and China use mostly coal while Mexico uses far more oil and gas (IPCC, 2005). The choices of energy source strongly affect CO_2 emissions, as coal has the highest carbon content per kWh of electricity produced, followed by oil, then natural gas. The residential and transport sectors contribute approximately 30% to worldwide CO_2 emissions. A further description of CO_2 sources is provided in Appendix 1A.

Although CO_2 is harmless to humans in small concentrations (such as those found in the atmosphere), higher concentrations can cause significant problems which are discussed in Section 2.3.6.

2.2 CARBON CAPTURE AND STORAGE

Carbon dioxide capture and storage (CCS) refers to the process of extracting CO_2 (generally from the flue gas of a fossil-fuelled power plant), compressing the gas and transporting it to a site for long-term geological storage, thus not releasing it to the atmosphere (Natural Resources Canada, 2006). CCS is an essential contributor to reducing GHG emissions and lessening the effect of anthropogenic climate change (IPCC, 2005). Climate change mitigation models have been used to show how CCS can significantly contribute to reducing anthropogenic climate change. A further description of climate change mitigation models is provided in Chapter 3 and Appendix 1B. CCS is an expensive technology and has few niche uses beyond mitigating climate change. Nevertheless, the IPCC considers CCS to be one of several options needed in the "portfolio of mitigation options for stabilization of atmospheric greenhouse gas concentrations" (IPCC, 2005 p3). As the evidence for anthropogenic climate change increases, research into CCS has increased commensurately. CCS refers to a process and not a single technology as there are many different technologies that can capture, transport and store CO_2 (Meadowcroft and Langhelle, 2010).

The key targets for CCS are power plants that emit more than 1 MT of CO_2 annually (see Table 2) and other large point sources of CO_2 (see Table 1). Moreover, these other large point sources also typically have relatively high CO_2 concentrations. Fossil fuel power plants and refineries account for the largest point sources. Large point sources have significantly higher CO_2 concentrations than diffuse sources such as automobile exhaust, and have a lower CO_2 capture cost per unit due to economies of scale. One possible way to mitigate emissions from smaller sources such as residential heating is to shift to processes that use electricity, with the energy coming from a CCS fossil fuel plant or a renewable energy source (Meadowcroft and Langhelle, 2010).

Table 2 CO_2 concentrations of large fossil fuel power plants (adapted from IPCC, 2005)

Source	CO_2 concentration % volume dry
Power station flue gas:	
Natural gas fired boilers	7-10
Gas turbines	3-4
Oil fired boilers	11-13
Coal-fired boilers	12-14
IGCC after combustion	12-14
Oil refinery and petrochemical plant fired heaters	8

There are three commercial-scale CCS projects operating worldwide as of 2010 with more, smaller demonstration and pilot plants being developed or proposed (see Figure 5). The three commercial projects are Sleipner in the North Sea near Norway, Weyburn-Midale in Saskatchewan, Canada, and In Salah in Algeria. Although commercial-scale, none of these projects fully integrate CCS with power plants (IPCC, 2005). As more pilot projects are introduced, the experience gained could result in eventual lowering of both costs and risks of CCS. Each of these projects is described in more depth in Appendix 1B.

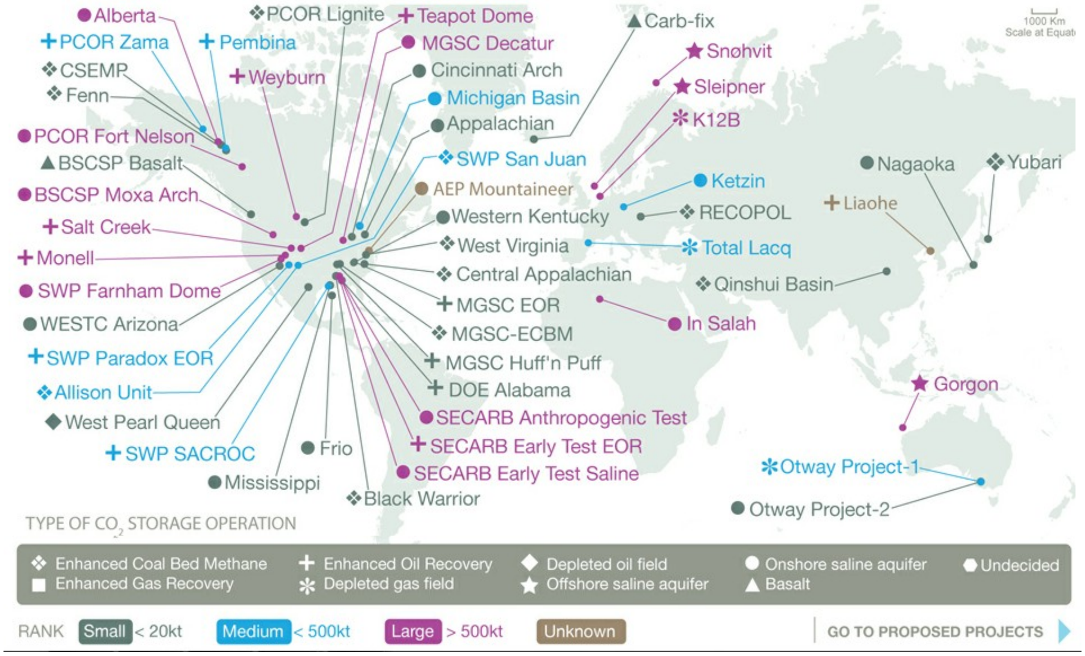

Figure 5 Location of major CO_2 storage, Enhanced oil recovery and research sites worldwide (CO2CRC, 2010b)

CCS allows for the continued use of affordable and available fossil fuels, without most of the associated GHG emissions (Natural Resources, 2006), while retaining the existing energy infrastructure. Canada has very large fossil fuel reserves and an established infrastructure committed to generating electricity with these reserves. Coal is at the center of many of the Provinces' power production strategies and is expected to remain a significant part of the energy mix for the foreseeable future (Natural Resources, 2008). Canada ranks third in the world for remaining conventional oil reserves behind only Saudi Arabia and Venezuela (CAPP, 2012) and second when unconventional oil reserves are included (NEB, 2004). Currently, 85% of global energy comes from fossil fuels, which is not expected to change drastically in the near future (Rackley, 2010). CCS therefore would allow energy producers to continue with business as usual (BAU) practices while more sustainable and long term climate mitigation strategies are developed. As Meadowcroft and Langhelle state, "The long-term future of fossil fuels is closely bound up with the development and deployment of CCS" (2010, p 8). If mid-century IPCC emission reduction targets are to be achieved, virtually all fossil-fuelled power plants would need to have a CCS component integrated into their system. Opponents of CCS argue that government investment in CCS may reduce funding to sustainable energy options related to renewable energy sources, which they view as more permanent solutions to climate change. They believe that CCS's drawbacks outweigh the benefits and cause collateral harm and potentially more CO_2 emissions in the long term (AOSIS, 2011). Governments are trying to achieve a balance between those for and against CCS and prioritize based upon domestic needs (EU, 2008, Doelle and Lukaweski, 2012). A further discussion of worldwide reserves and infrastructure can be found in Appendix 1B.

Certain aspects of CCS have been in use for decades to recover oil and gas from geological reservoirs. Enhanced oil recovery (EOR), an increasingly popular option for implementing CCS, was first developed in the U.S. in the 1970s as a way of using excess CO_2 to extract more oil from existing fields (IPCC, 2005, DOE, 2009). EOR involves injecting CO_2 into oil and gas wells to re-pressurize reservoirs, reduce the oil's viscosity thus yielding more oil and gas (see Figure 6). The process also loosens up residual oil by reducing the surface tension of oil within the surrounding reservoir allowing for easier movement (Meadowcroft and Langhelle, 2010). Approximately 30 Mt of natural CO_2 is injected into oil fields annually (mostly in Texas) with other small projects existing throughout the world. There are over 50 individual EOR sites worldwide, some of which have been in use since the 1970s (IPCC, 2005). The high number of EOR sites is due to the changing economic conditions that led to the process becoming viable within the past four decades. Oil fields typically include a wide spectrum of petroleum oils ranging from very heavy tar-like substances (such as those found in Canada's oil sands) to very light hydrocarbons and gases such as CO_2 and methane. In those cases where CO_2 exists, this CO_2 is taken directly from an oil field to re-pressurize the same or nearby oil fields and thus yield more extracted oil overall. In many cases, however, the CO_2 for EOR is taken from naturally occurring CO_2 reservoirs elsewhere, combining the transport and injection aspects of CCS which is explored further below (Rackley, 2010).

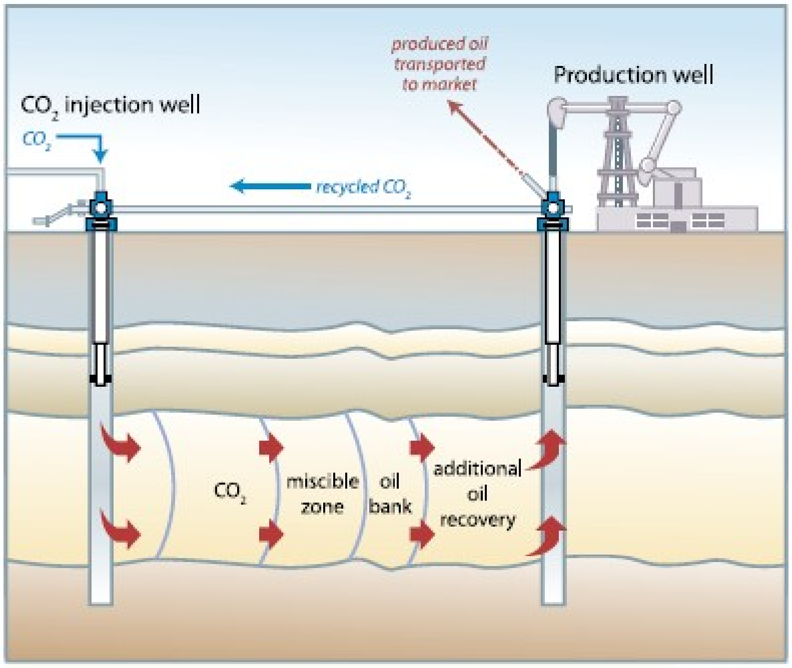

Figure 6 Enhanced oil recovery using injected CO_2 to pressurize declining oil and gas reservoirs and increase their production (IPCC, 2005)

EOR is usually the tertiary oil recovery method after first using primary production and then water flooding. Normal primary production removes between 5 and 40% of the oil, with water flooding adding another 10-20% and finally CO_2 injection a further 7-23% (IPCC, 2005). As oil and gas prices increase, EOR becomes increasingly economically viable (and by association so do some CCS projects). Although EOR has been in use for many decades, using CO_2 for enhanced natural gas recovery is relatively new and still in the pilot testing phase.

In order to match CCS projects and EOR, CCS projects (and pipelines) will need to be timed and located to meet the needs of declining oil wells so that the wells can be used most efficiently (IPCC, 2005). It will be much less expensive to conduct EOR while extraction wells are still in production since much of the equipment and personnel will already be available.

As mentioned above, EOR provides several benefits beyond producing more oil and gas; the infrastructure used in oil and gas exploration and development can be of great use in transporting and injecting CO_2 into exclusively storage sites. Subsurface formations for use in CO_2 storage without EOR can become well characterized in petroleum fields (IPCC, 2005). Data collected and infrastructure from EOR projects, combined with computer modeling, can allow for accurate assessments of potential for CO_2 injection for EOR, as well as strict CO_2 storage.

2.2.1 CO_2 Capture

A significant portion of the costs of post-combustion CCS is due to the difficulty in extracting relatively low concentrations of CO_2 from flue gas emissions (in order to purify it to the high concentrations required for capture, transport and storage). The lower the concentration of CO_2 in the flue gas stream, the more energy and thus cost is required in the capture process

(IPCC, 2005). The low CO_2 concentrations for several typical CO_2-emitting processes are shown in Table 2. Most emissions from power generation and industrial processes have relatively low CO_2 concentrations (although still much higher compared to atmospheric concentrations and those from other processes) and thus engender high capture and compression costs (IPCC, 2005). Despite the cost limitations, current technology can capture up to approximately 85-95% of the CO_2 produced in the flue gas from fossil-fuelled power plants, depending on the fuel input and the capture technology, which is explained below and in Appendix 1B.

There are three major types of CO_2 capture technologies used in CCS: post-combustion CO_2 capture, pre-combustion CO_2 capture, and oxyfuel CO_2 capture. As post-combustion capture technologies are the most mature and widely used currently, they were chosen as the capture technology for the scenarios in this thesis. A further description of the other CO_2 capture methods can be found in Appendix 1B. As the CCS field develops, the other capture technologies are expected to become more widespread in commercial-scale projects. The key differences between the methods relate to when CO_2 is captured from the system during the combustion process and whether the fossil fuel is combusted in the presence of atmospheric air or pure Oxygen (O_2). A schematic of the different methods of combustion, separation and compression of CO_2 for the three capture types is shown in Figure 7. The main advantages and disadvantages of each of the capture technologies are outlined in Table 3. Post-combustion CO_2 capture holds the most promise for near-term deployment and retrofit opportunities, while pre-combustion and oxyfuel combustion may have significant advantages within specific applications of CCS in the long-term once technological and economic hurdles can be overcome.

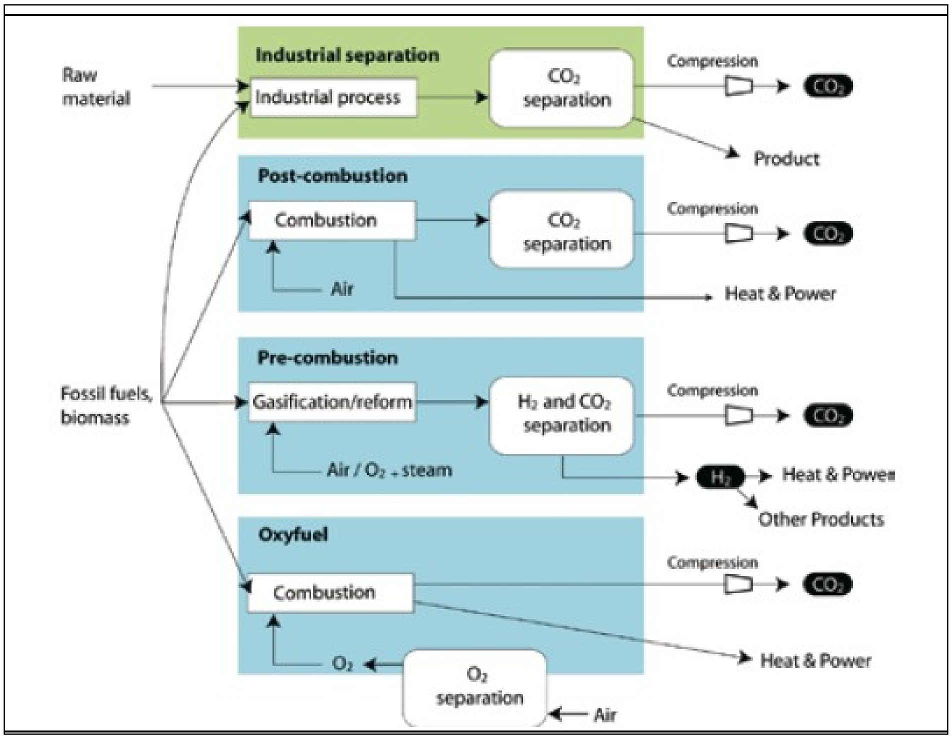

Figure 7 Schematic diagram of the different major CO_2 capture processes (IPCC, 2005)

Table 3 Advantages and disadvantages of capture technologies (Rackley, 2010)

Capture option	**Advantages**	**Disadvantages**
Pre-combustion	• Lower energy requirements for CO_2 capture and compression	• Temperature and efficiency issues associated with hydrogen-rich gas turbine fuel
Post-combustion	• Fully developed technology, commercially deployed at the required scale in other industrial sectors • Opportunities for retrofit to existing plants	• High parasitic power requirement for solvent regeneration • High capital and operating costs for current absorption systems
Oxyfuel combustion	• Mature air separation technologies available	• Significant plant impact makes retrofit less attractive

Post-combustion capture technologies are the most developed CO_2 capture method and are already in use in several pilot and demonstration plants worldwide. This capture method has also been in use for several decades in the natural gas processing industry (IPCC, 2005), although there is much less experience in capturing CO_2 from power plants (Rai *et al.,* 2009). Post-combustion refers to collecting CO_2 gas from the flue gas after the fuel has been burned. The capturing therefore takes place in the flue gases and is similar to other processes involving "scrubbing" pollutants out of the smokestack such as those for removing sulphur oxides (SO_x) and nitrogen oxides (NO_x).

The typical flue gases from a fossil-fuelled power plant are shown in Appendix 1B along with their respective concentrations. These concentrations and other parameters are important for post-combustion capture because they determine how the CO_2 will be removed and purified before transportation. Variations in these characteristics can greatly change the feasibility and economics of a CCS project. For instance, the CO_2 must be transported in isolation from other chemicals such as water and sulphur, which impact the capture efficiency, thus high concentrations of other chemicals can significantly increase the capture cost. By contrast, pre-combustion capture and oxyfuel CCS allow more control over the conditions under which CO_2 is combusted or released, to make capturing CO_2 less expensive. A description of different methods applied to cement plants, which like fossil-fuelled power plants have high CO_2 emissions and may be suitable for CCS, can be found in Appendix 1B.

2.2.2 CO_2 Transportation

The main types of CO_2 transportation include truck, boat and pipeline. For relatively small quantities on the order of hundreds of tonnes of CO_2 per year, trucks may be the least expensive option (IPCC, 2005 and IPCC, 2006). For distances that are up to 1,000 kilometres and those that involve larger quantities of CO_2, pipelines are the preferred option. For overseas transportation, ships can be the most economically attractive option (see Figure 8) (IPCC, 2005). As CO_2 transport via pipeline is currently the most widely used transportation method, it is used as the primary method throughout this thesis.

CO_2 purity is important both for capture technologies, as well as in transport and storage, since impurities change the compressibility of the gas. CO_2 must be compressed for transportation to enable large volumes of the material to be transported in small pipelines to improve efficiency and reduce costs. Components such as SO_x, NO_x and Hydrogen sulphide (H_2S) may result in the transported fluid being classified as hazardous, depending on their concentrations, requiring special handling and disposal methods (Bergman *et al.,* 1997). Pipelines also have limits on impurities (including water) as they can affect the structural integrity of the walls mostly due to corrosion; CO_2 is therefore always dehydrated prior to transportation (Meadowcroft and Langhelle, 2010).

Power plants are typically not sited based on adjacency to suitable geological storage for CO_2, but rather based on proximity to a fuel supply source or a centre of concentrated energy demand. The distances between the CO_2 source and geological storage site can thus be on the order of several kilometres to hundreds of kilometres away. Research into suitable storage reservoirs is still very limited.

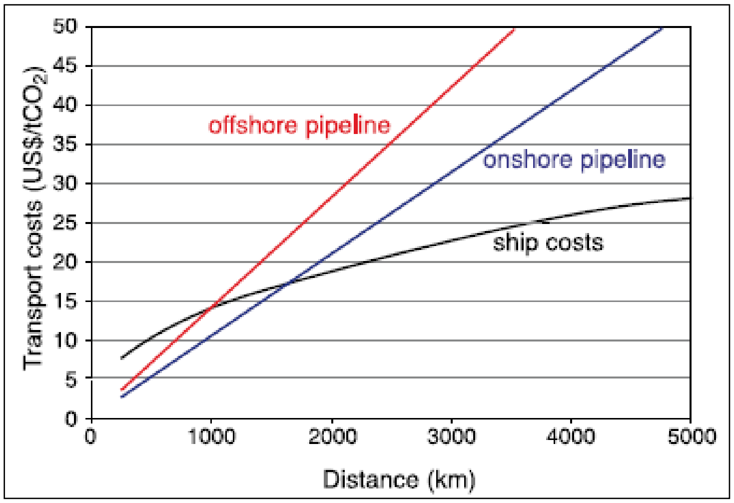

Figure 8 Costs of transporting CO_2 by method and distance (IPCC, 2005)

Transport of CO_2 by pipeline has been occurring for many years and operates in a mature market with over 6,500km of pipelines comprising 36 separate pipelines in the United States alone (see Figure 9) (IPCC, 2005; Interstate Oil and Gas Compact Commission; DiPietro and Balash, 2012). There are CO_2 pipelines in other countries, although the industry is far less developed. On shorter pipelines, an upstream compressor pushes the CO_2, whereas longer pipelines require periodic compressors along the route to ensure adequate pressure throughout (IPCC, 2005). The technologies, risks and costs associated with transporting CO_2 are not expected to be a barrier to CCS implementation, as these are minimal and well known. In comparison, CO_2 capture and storage in geological formations is a novel research area that requires significant future research to reduce uncertainties and risks associated with the injection of large quantities of CO_2.

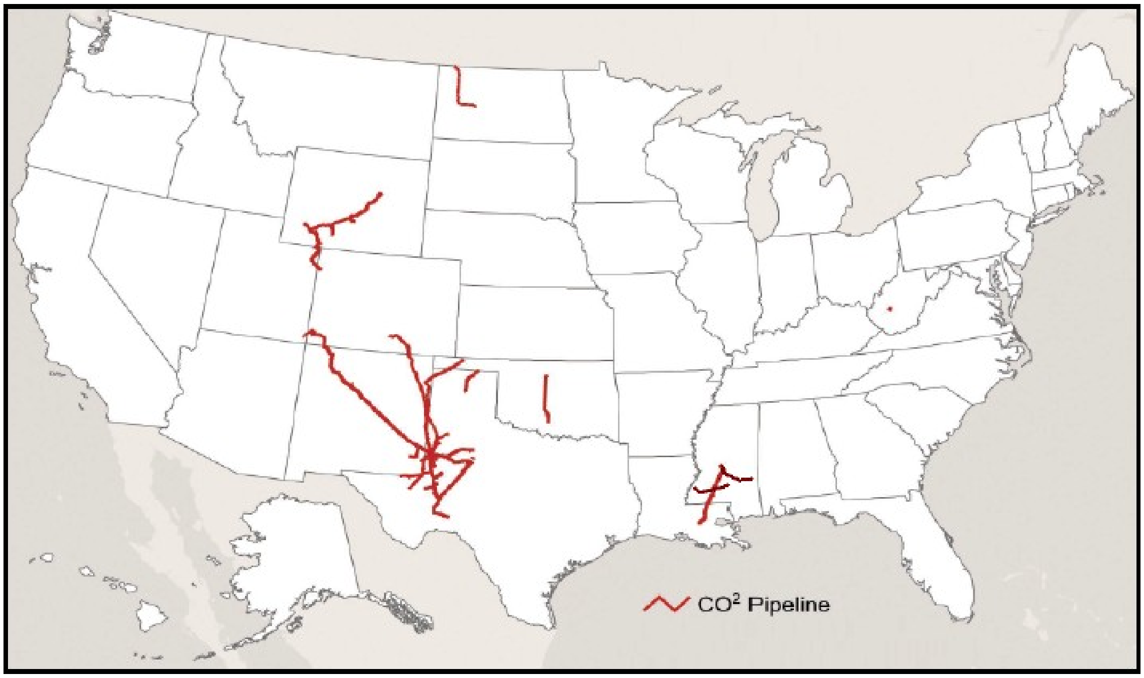

Figure 9 CO_2 pipelines in the United States (Parfomak and Folger, 2008)

2.2.3 CO_2 Storage

Research has shown that the sites with the most potential for CO_2 storage occur in depleted oil and gas fields, coal-bed methane reservoirs, deep saline aquifers and salt caverns (see Figure 10) (Natural Resources Canada, 2006). These natural geological sites trap CO_2 in reservoirs surrounded by an impermeable layer, or cap rock, so that the CO_2 does not migrate laterally or vertically. After tens to hundreds of years, the CO_2 may be chemically and physically bound to the surrounding media in the reservoir. There may also be significant storage capacity offshore in similar geological formations although this is less well studied. All these storage options involve injecting CO_2 into dense rock formations up to several kilometres below Earth's surface. Suitable storage sites have been identified in both onshore and offshore locations (IPCC, 2005). All these storage sites represent ancient depressions that have filled with sediments and formed sedimentary rocks, however preliminary work is being undertaken to study storage in igneous and metamorphic rocks, which have much lower porosities. Direct mineral fixation[4] is another CO_2 storage option but would likely be prohibitively expensive and environmentally damaging (Natural Resources Canada, 2006).

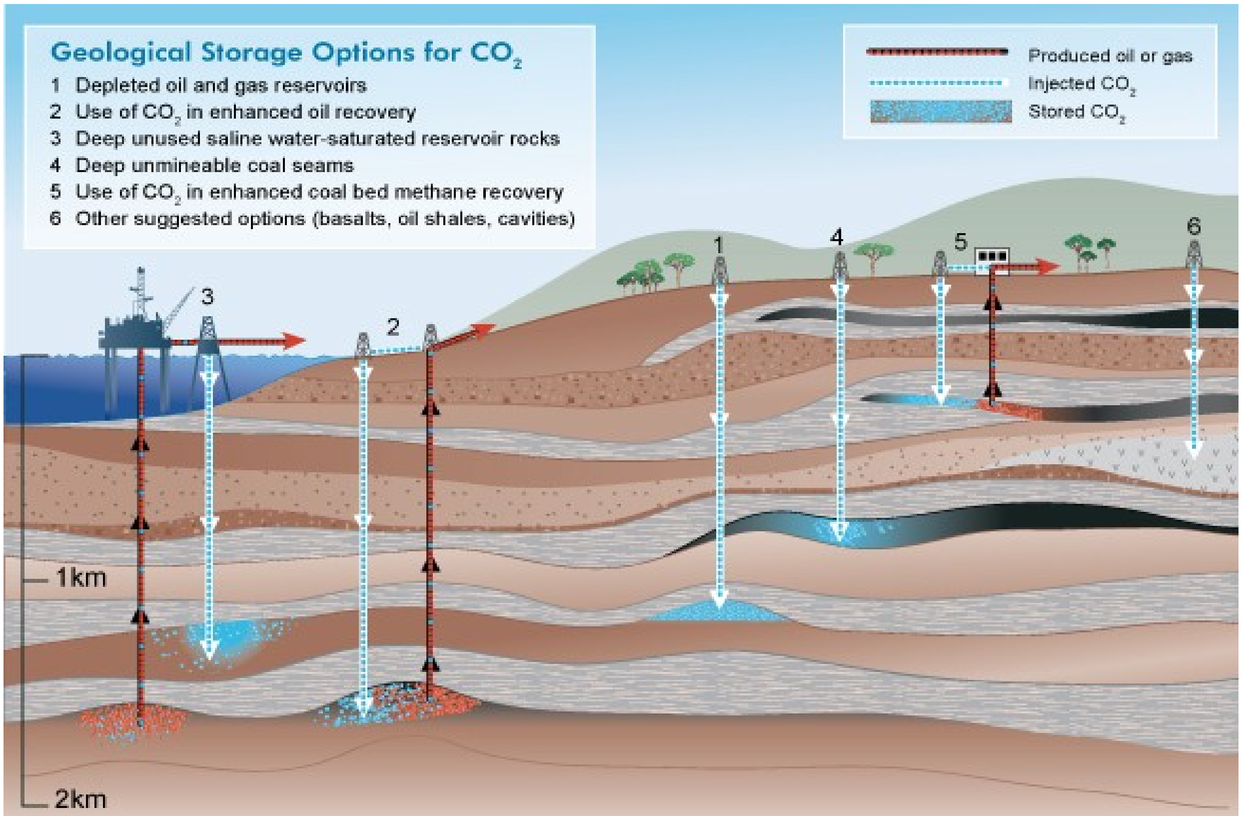

Figure 10 Geological storage options for CO_2 (CO2CRC, 2008a)

There has been a significant amount of experience gained in CO_2 storage by the petroleum industry through their work in EOR (IPCC, 2005). Using this knowledge it is expected that

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[4] Mineral fixation is the reaction of CO_2 with minerals to create carbonates that are geologically stable. There are many methods of injecting and promoting the reactions which are generally very slow, however research is being conducted to improve the processes (Goldberg *et al.,* 2000).

injecting CO_2 into well-characterized and properly selected sites is will be very secure, with 99% of the injected CO_2 remaining underground for at least 1,000 years (IPCC, 2005).

The types of storage reservoirs vary considerably in location, storage capacity and the storage mechanism used. While initial estimates show that there is potentially more than enough storage space to contain all anthropogenic CO_2 emissions in geological reservoirs, there still are many other factors to assess when considering total practical storage capacity. In order to make significant reductions to atmospheric CO_2 concentrations there will need to be hundreds to thousands of large-scale CO_2 storage sites (IPCC, 2005). Some of these storage sites will be in locations too remote or too expensive to feasibly and efficiently store CO_2 (IPCC, 2005). Fortunately, most population centres lie above or near sedimentary deposits (as they are generally nutrient rich and flat) so many storage sites are expected to be located near the CO_2 source. Associated environmental and health risks are described in Sections 2.4.2 and 2.5. The general distribution of different basins for potential CO_2 storage worldwide is shown in Figure 11. The size of the sedimentary basins or the size of the storage site does not necessarily indicate that the site is suitable for CO_2 storage.

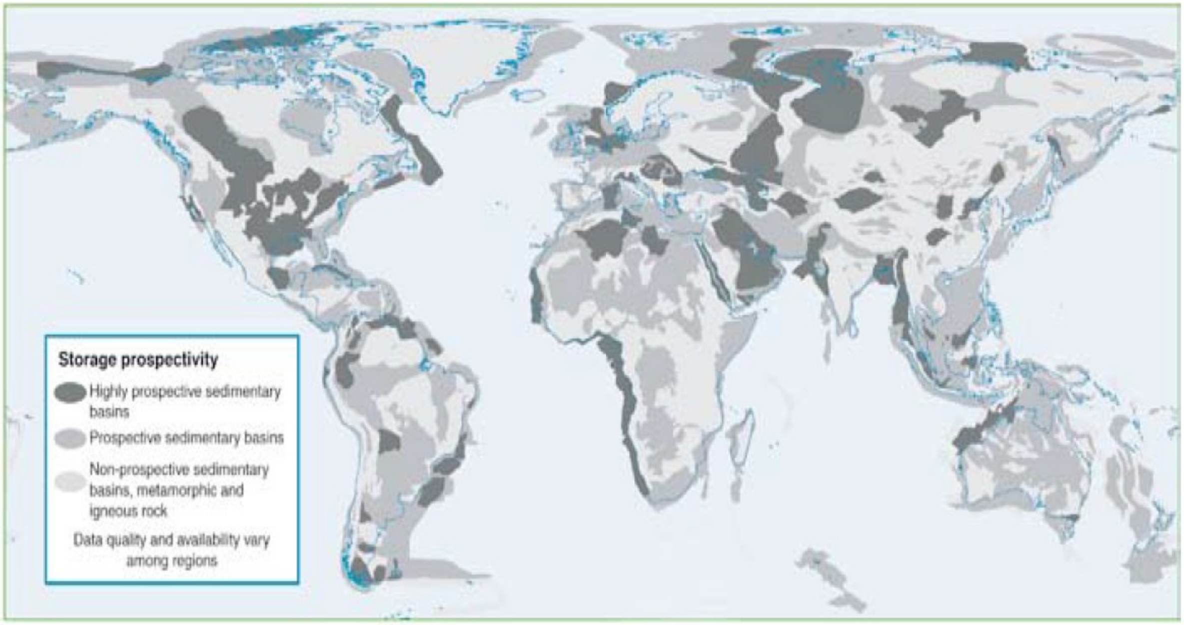

Figure 11 Distribution of prospective sedimentary geological basins worldwide for CCS CO_2 storage (IPCC, 2005)

Detailed studies of storage areas within countries are still in the early stages of analysis. Preliminary results show that many CO_2 storage sites are situated near emission sources. In Canada, thorough studies have only been conducted in the Western Canadian Sedimentary Basin (WCSB) with limited research elsewhere. The WCSB is expected to have many CO_2 emission sources with suitable storage sites nearby in southern Alberta and Saskatchewan. The oil sands in northern Alberta, however, are not near suitable sites and CO_2 would have to be transported further distances (Bachu, 2003). Refineries are now being built near Edmonton in Northern Alberta, which will much more closely link emission sources with storage sites. As discussed in Appendix 1B, a proposed network of pipelines in the WCSB to connect with the oil sands may solve this problem.

2.2.3.1 CO_2 Storage Mechanisms

CO_2 is typically injected at depths between 800m and 2km because at these depths, temperatures, and pressures, it compresses into a very dense supercritical fluid that efficiently fits into the pore space of sedimentary rocks, with density varying as a function of depth. The diverse types of storage mechanisms (mineral, solubility, residual, structural and stratigraphic trapping) are described further in Appendix 1B. These mechanisms often work in concert, resulting in more security of CO_2 storage over time as more mechanisms trap CO_2 (see Figure 12) (IPCC, 2005). Although there are different methods of securely storing CO_2 in the subsurface, all CO_2 enters the same way: through well injection into pore spaces between grains and minerals, and into fractures. Injected CO_2 displaces the *in situ* fluids (IPCC, 2005), which is useful for enhanced oil recovery. For EOR, not all CO_2 will remain underground as some is re-extracted with the oil to be reused to extract further oil.

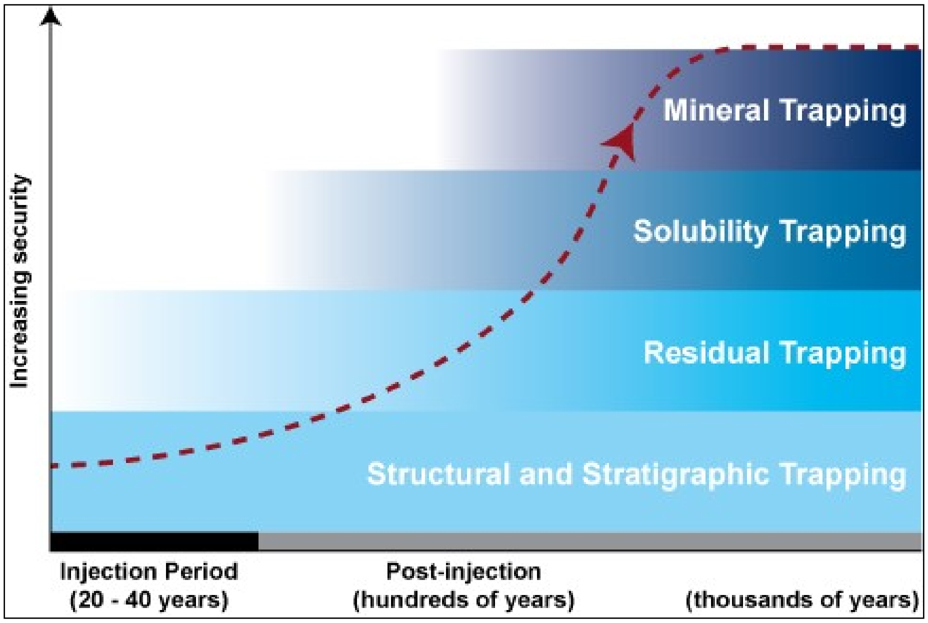

Figure 12 Security of CO_2 in geological storage as a function of time (CO2CRC, 2008b)

2.2.3.2 Monitoring and Verification

Monitoring provides many benefits such as verifying that CO_2 is stored properly and is not leaking out of the reservoir, and optimizing the efficiency of storage. It can also determine which methods of storage are the most effective (IPCC, 2005). Accurate measurement and monitoring of stored CO_2 is important for CCS as it was recently approved as a Clean Development Mechanism (CDM) technology. The CDM is a flexibility mechanism of the Kyoto Protocol that enables developed countries to reduce or sequester GHGs in developing countries in order to offset emissions from domestic sources and avoid non-compliance with their Kyoto Protocol GHG reduction targets (IPCC, 2007). Companies are able to buy GHG credits for emissions that they produce and sell credits that are no longer emitted. At the Durban conference in 2011, the member parties agreed that CCS could be considered under the CDM and will review unresolved regulations related to trans-boundary transport and storage of CO_2 in subsequent conferences (UNFCCCb, nd). CDM emission credits could greatly improve the economic viability of CCS by creating a marketplace for geologically stored CO_2.

Proper baseline studies of storage basins are essential to determine what effect CO_2 injection may have on the surrounding environment (both surface and subsurface). The technology that has been used to map and estimate petroleum deposits can be adapted towards monitoring and verifying CO_2 storage (IPCC, 2005). Nevertheless, even with this technology the interactions and movement of CO_2 in the subsurface are difficult to determine prior to injection. Geological storage formations are heterogeneous so CO_2 will not disperse uniformly, complicating the storage characterization process (Emberley *et al.,* 2002). Once injected CO_2 reaches a production or monitoring well, the CO_2 distribution can be more easily determined. The Weyburn-Midale project (one of few CCS research projects) injected CO_2 underground with an isotopic composition different than the natural CO_2, so that monitoring and production wells that come into contact with injected CO_2 and are able to show the extent and timing of the migration (Emberley *et al.,* 2002). Other monitoring techniques that are used include gravity measurements, land surface deformation, infrared imaging, soil gas sampling and seismic testing. Although monitoring and production wells are the most effective methods of characterizing CO_2 storage, they are also the most invasive (and expensive) and can result in more potential leakage pathways (Emberley *et al.,* 2002). Tracers such as exotic gases and isotropically different chemicals (than those naturally found in the formation) can be injected along with the CO_2. Then, the formation fluid can be more easily analyzed to determine how the system is responding to the injected CO_2.

2.2.4 Energy Penalty

The process of capturing, compressing and transporting CO_2 from a power plant requires a significant amount of energy, thus resulting in what is referred to as an energy penalty. Approximately 10-40% additional energy is required to produce electricity from a power plant with CO_2 capture as compared with a similar plant without CCS, depending on the conditions and the technology used. This wide range is due in part to the still-immature integration of CCS capture technologies, as well as the different types of plants: for natural gas combined cycle plants, the range is 11–22%, for pulverized coal plants, 24–40% and for integrated gasification combined cycle plants, 14–25% (IPCC, 2005). The energy penalty for a typical power plant with and without a CCS unit attached is shown in Figure 13. Although a CCS plant can capture up to 95% of the CO_2 emitted, due to the energy penalty more fuel is burned and thus there is more generated CO_2 to be captured (relative to a plant without CCS), resulting in a slightly lower capture percentage overall. For example, if a traditional fossil-fuelled plant emits 100kg of CO_2, a comparable power plant with CCS would generate up to 140kg of CO_2 emissions when producing the same amount of electricity. Capturing 95% of these emissions results in 133kg of CO_2 diverted and 7kg of CO_2 still emitted for an overall maximum efficiency of 93% relative to the original flows. Thus a CCS plant rated at between 85% and 95% capture is actually between 80% and 90% efficient at removing CO_2. The reduction in CO_2 emitted with a traditional plant relative to a CCS plant is termed "CO_2 avoided".

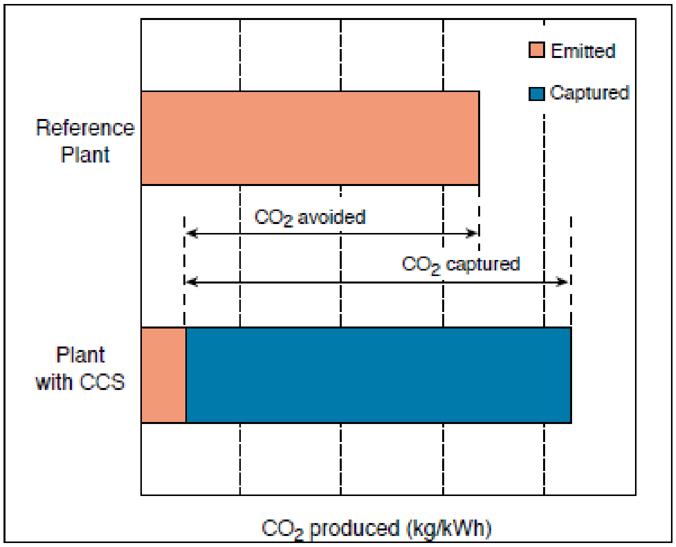

Figure 13 Energy penalty associated with power plants with CCS attached (IPCC, 2005). The energy penalty is the difference between the CO_2 emissions of a plant with CCS and a reference plant.

2.3 FACTORS IMPACTING CCS

There are many factors that need to be overcome before widespread CCS deployment can occur. As described below, these CCS-factors include economics, environmental, social perceptions, government policies, and competition with alternative climate change mitigation strategies.

2.3.1 Economics of CCS

The estimates for the cost of CCS vary widely due to many factors including location, type of capture technology, transportation distances, storage media, government regulations, tax incentives, and fuel and material costs. The cost of capturing CO_2 is by far the most expensive portion of CCS. Generally, the incremental cost estimates of producing electricity with CCS power plants range from 1.8-3.4US$ct/kWh[5] for pulverized coal CCS power plants, 0.9-2.2US$ct/kWh for integrated gasification combined-cycle CCS power plants, and 1.2-2.4US$ct/kWh for natural gas combined-cycle CCS power plants. The costs of transporting and storing CO_2 vary between -1.0 and 1.0US$ct/kWh. The possibility of negative storage costs is due to the use of captured CO_2 for EOR or enhanced coal-bed methane (ECBM), which generates some income from the process (IPCC, 2005). These CCS costs can be compared to Canadian electricity prices that currently range from approximately 7-17US$ct/kWh (NEB, 2012).

Once the least-cost climate change mitigation options are exhausted, such as energy efficiency and conservation, CCS will become increasingly competitive against alternatives such as increasing nuclear power and renewable energy technologies. The threshold when CCS becomes competitive against alternative climate change mitigation options is expected to be when there is a carbon emission reduction credit for storing CO_2 that is at least 25–30US$/t$CO_2$ (IPCC, 2005), though this may have to be much higher depending on how CCS and competing technologies develop. The carbon emission reduction credit works by paying a CCS installation a sum of money for each tonne of CO_2 that is geologically stored and thus not released to the atmosphere.

One of the risks associated with storing CO_2 is not finding a suitable storage site nearby. Although the fundamentals of geological storage of CO_2 are fairly well known, there is still a risk that money could be spent on a fruitless search for storage sites, or that possible CO_2 leaks

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[5] Electricity prices are usually referred to in US$ct/kWh which is United States cents per unit of energy used during one hour (kilo watt hours, kWh).

from storage reservoirs could result in lost revenue from CO_2 storage credits, remediation costs, as well as damage to people and the environment (Global CCS Institute, 2009). Even after CO_2 storage sites are found, there can be unexpected costs due to unforeseen reservoir characteristics, such as low CO_2 injectivity, which can result in further wells needed for injection, or, even worse, abandonment of the project.

2.3.2 Environmental Concerns of CCS

Environmental and health risks associated specifically with CO_2 leakage from geological storage are discussed in Section 2.5. Other environmental effects of CCS are discussed here.

Although current CCS technologies can reduce CO_2 emissions from fossil-fuelled power plants by approximately 85% (IPCC, 2005), the CO_2 emissions are only one of the environmental impacts from these plants; land use, mining, acid rain, noise, water use and solid waste are some of the other drawbacks of fossil fuel production which can be increased by the development of CCS. Injecting CO_2 into the ground may cause micro-seismic events, similar to those associated with hydraulic fracturing (Suzuki, 2012). The greater fuel demand for CCS, due to the energy penalty, increases most other environmental emissions per kWh such as mercury, solid wastes and other environmental impacts from mining the fossil fuels (IPCC, 2005). Depending on the type of capture technology employed there may also be increased demand for chemicals such as ammonia and limestone to control sulphur dioxide and nitrogen oxide that would otherwise not be required without CCS, as well as the materials used in the construction of the capture portion of CCS. Capture media are often volatile and are released into the atmosphere through flue gases as they degrade and break down. Depending on the capture media, pollutants other than CO_2 are sometimes collected as well (IPCC, 2005). All the fuel input and construction materials, including cement production used in the construction of CCS facilities, will be increased due to more power plants being required (or larger ones) to produce the same amount of electricity due to the energy penalty. Improvements in CCS efficiency will help reduce these environmental concerns but will not completely eliminate them (IPCC, 2005).

2.3.3 Social Concerns/Public Perception of CCS

Public perception of CCS in general and acceptance of local CCS projects has varied widely which has led to some projects being cancelled or postponed (Ashworth *et al.,* 2010; Desbarats *et al.,* 2010; Anderson *et al.,* 2012). Studies have shown that after the introduction of an information campaign on CO_2 storage options, the opinions of the public varied; in some, tolerance increased, while in others the acceptance of geological and ocean storage actually decreased (Palmgren *et al.,* 2004). All studies so far have shown that if CCS is chosen as a climate change mitigation option, there is preference for subsurface geological storage onshore and offshore rather than storage at the bottom of oceans above the sea bed.

There are many benefits and drawbacks of living near a CCS plant with local residents often having NIMBY attitudes. Electricity prices are an issue that affects the public even if they are not situated near to a CCS project. Although the costs of CCS are an economic issue initially borne by the project owner, ultimately the increased cost of electricity will affect all energy users. Higher electricity prices will impact the public unevenly according to their dependence on electricity, and their capacity to afford cost increases may degrade views of CCS. Conversely, although there will be increased costs associated with CCS, some types of air pollution near power plants may be slightly lowered and new jobs will be created (IPCC, 2005).

Pipelines will necessarily have to span varying distances between power plants and storage reservoirs. Some of these pipelines will inevitably interfere with human activities and settlements with the possibility of CO_2 leaks, habitat fragmentation, property value depreciation and health concerns. CO_2 pipeline risks and concerns are addressed in Section 2.5, but are expected to be of even less concern than existing natural gas or oil pipelines as CO_2 is not flammable or explosive and will not require extensive cleanup measures. Although the probability of pipeline failure is very low, the consequences of that failure can still be quite high (IPCC, 2005). New oil and gas pipelines have been proposed in more extreme locations such as remote mountainous regions (which are difficult areas to remediate if a leak occurs) and have been met with strong opposition, including public demonstrations (Vanderklippe, 2012). CO_2 pipelines can expect similar opposition when not sited within industrial areas.

Non-Governmental Organizations (NGOs) have been very vocal in their support or opposition of CCS. The Bellona Foundation, a Norwegian anti-pollution organization, has supported CCS under the justification that it is one of the few technologies that can make deep cuts to CO_2 emissions (Meadowcroft and Langhelle, 2010). Greenpeace, on the other hand, has consistently criticized CCS, especially in their 2008 report “False Hope: Why Carbon Capture and Storage won’t Save the Climate” which gives the following five reasons: “CCS is a dangerous gamble”, “CCS won’t deliver in time to prevent climate change”, “CCS wastes energy”, “CCS is expensive and undermines funding for sustainable solutions”, and “there are significant liability risks” (Greenpeace, 2008). Due to the close association of CCS with the fossil fuel industry many people are sceptical about the technology and believe it is a ploy by climate change deniers to delay real action (i.e. weaning the world off of fossil fuels) (Risbey, 2008). Some critical studies and press reports have left a negative image that CCS would have to overcome in order to become widely accepted and gain government support (Stigson *et al.,* 2012).

CCS remains a divisive climate change mitigation strategy with its potential for significant emission reductions but also high costs and potentially large negative impacts. The development of CCS will be strongly tied to public perception of CCS which can delay, cancel or impact government funding. Early demonstration and pilot projects will provide insight into how this may unfold.

2.3.4 Government/Policies for CCS

Worldwide there are virtually no national regulations concerning CO_2 storage. CCS is a capital-intensive industry where legislation and policies can significantly impact development but which has lagged behind technological developments (especially in the U.S.) (Meadowcroft and Langhelle, 2010). There are, however, many regulations relating to the geological storage of water, gas, and oil that can be modified to pertain to CO_2 capture, transport and storage (IPCC, 2005) (e.g. the Australian *Offshore Petroleum and Greenhouse Gas Storage Act 2006* (Energy, Resources and Tourism, 2006)). Individual states and provinces have taken the lead to develop some regulations such as the *Carbon Capture and Storage Statutes Amendment Act 2010 (Alberta, 2010)*.

If CCS is to be effective as a climate change mitigation technology, it will need to be adopted on a large scale worldwide. Due to the high costs and large uncertainties, a coordinated approach should be made to research and develop CCS. International developments will strongly affect how CCS is perceived and developed in Canada. Canada, the U.S., U.K. and Australia are leading CCS research and development. A description of how CCS impacts, and is impacted by, the international community is provided in Appendix 1B.

Energy and economic models of the costs of CCS indicate that without the implementation of explicit policies promoting the technology, CCS will not be deployed at a large scale in the foreseeable future (IPCC, 2005). Oil and gas companies are hesitant to implement CCS projects unless their competitors are also required to do the same. Currently only small niche opportunities are being developed for CCS, such as for emission sources with very high CO_2 waste streams and those involving EOR and ECBM. In order for CCS to be financially viable, there will also need to be substantially more stringent limits on greenhouse gas emissions. Currently, CCS is not economically viable as there are less expensive small-scale climate change mitigation options available such as increased conservation and energy efficiency (IPCC, 2005).

As taxes on carbon emissions rise or CO_2 emission limits become stricter, increasing numbers of CCS projects will become economically viable.

The extended time horizon of CCS, and its mismatch with that of institutions and companies, is an additional challenge for CCS. The long term liability of storing CO_2 and ensuring that it does not leak is one of the last major technical obstacles remaining for CCS (Dixon, 2009). In order to be an effective climate change mitigation option, CO_2 must be sequestered for thousands of years, which far exceeds the lifespan of any corporation or political system. Questions therefore remain about who will be responsible for the long term storage of CO_2. If it can be shown that CO_2 is highly unlikely to leak, or if proper legislation is developed for storage liability, then CO_2 leakage will be less of a factor for implementation decisions.

Another barrier to CCS development is the dearth of regulations and legislation for CCS development. The IPCC has developed guidelines for storing and monitoring CO_2, as have the government of Alberta and Australia (Alberta 2010; Energy, Resources and Tourism, 2006). There are also several international treaties that concern the storage of CO_2. The London Convention and Protocol (1972) concern the disposal of wastes and other matters at sea and does prohibit some types of CCS projects. The London Protocol Amendment (1996) directly addresses CCS and provides restrictions on the types and methods of sequestering CO_2 in ocean environments (Dixon, 2009). The OSPAR Convention (1992) also addresses CO_2 storage in seas near Europe with an emphasis on protecting the marine environment (IEA, 2012). Although there are no international treaties concerning CO_2 storage on land, as CCS is expected to become more widespread, more international treaties and conventions will address aspects of CCS and CO_2 storage (Baker and McKenzie, 2011).

The extent to which CCS may expand as a climate change mitigation strategy is very uncertain. The two major unknowns facing CCS are how quickly and how much the costs of CCS will decrease, and the degree of government and public acceptance of CCS as a climate change mitigation option. Given the cost and scale of CCS, there is no reason for implementing the technology other than as a climate change mitigation option. The support of governments in either monetary or legislative terms is therefore essential for its development (Rai *et al.,* 2009). Past experience has shown that the public can turn against a technology if they do not believe that proper regulation is ensuring that private interests are not trumping those of the public (Meadowcroft and Langhelle, 2010). The establishment of international standards, rules on responsibility for leakage, and safe operating procedures will be essential for widespread market penetration. As CCS is a relatively new technology, significant legislative developments are expected in the near future. A description of how CCS may develop is shown in Appendix 1B.

2.3.5 Competition with Alternative Climate Change Mitigation Strategies

CCS competes with other climate change mitigation strategies for funding and support (Suzuki, 2012). Nuclear power for instance is one alternative option that can be deployed at a large scale with existing technology. The major obstacles facing nuclear power are uncertainty about cost, public perception and government regulations (IPCC, 2005), as well as a probability (albeit low) of large negative impacts. Uncertainty can be defined as a state in which there is a lack of information (partial or complete) related to the outcome of an event (ISO, 2009b). These uncertainties led to long permitting delays, and in some countries even moratoria on types of power generation such as nuclear power (Spiegel, 2011; Reuters, 2011; Terwel *et al.,* 2012)).

Many of the renewable energy options such as wind, solar, biomass, geothermal, hydro and tidal power could also be effective climate change mitigation options. Renewable energies' main drawbacks include intermittency, specific geographic requirements, scalability, infrastructure requirements and costs. The renewable energy options are however growing rapidly in scale due to improvements in technology and decreasing costs (IPCC, 2005). There is concern that some governments are funding CCS projects at the expense of renewable energy solutions which could more efficiently and economically reduce CO_2 emissions (Harvey 2012; Royal Society of Chemists, 2010). A major study by Pacala and Socolow (2004) suggest that CCS could be a major contributor to climate change mitigation by reducing global emissions by 100 $GtCO_2$ by 2060. Wind, nuclear and geothermal power generation all have been estimated to more cost-effectively reduce the same quantity of emissions but also to provide increasing revenue as their technologies improve (Royal Society of Chemists, 2010). Some energy scenarios suggest that CCS may be economically comparable to some types of renewable energy in the near future and reduce CO_2 emissions more than if they had not been included (Viebahn, 2007; Viebahn *et al.,* 2007). Others have found that CCS may integrate well with intermittent renewable energy technologies and produce synergies by providing stable base-load electricity from CCS power plants with low CO_2 emissions to balance intermittent renewable energies with no CO_2 emissions (Chalmers and Gibins, 2006).

The widespread use of renewable energy is problematic despite improvements in technology. Current electricity grids are not optimized to incorporate large quantities of intermittent electricity production. However, as renewable technologies improve and these problems (intermittency and storage) are resolved, they will gradually replace fossil fuel power production. Unfortunately, climate change mitigation models show that renewable and sustainable energy development will not occur on a large scale until the later part of the 21st century (IPCC, 2005). CCS is thus well-positioned to take advantage of the existing infrastructure and fossil fuel supplies to nevertheless abate the CO_2 problem until more permanent solutions can be developed.

Unlike the above alternatives, some niche mitigation options such as energy conservation and improved efficiency provide solutions that can reduce CO_2 emissions by 15% using existing technology and at a profit (IPCC, 2001a). A further 15% reduction in CO_2 emissions can be achieved with mitigation options that are only marginally more than cost neutral such as better collaboration and integration of electricity markets (IPCC, 2001a). As with all options, costs then increase as these niche options are exhausted and more challenging mitigation options must then be pursued. A method for estimating the costs of implementing climate mitigation strategies is called a Marginal (carbon) Abatement Cost Curve (MACC) (Ellerman and Decaux, 1998). MACCs evaluate the cumulative emission reductions of multiple mitigation options and recommend priorities for ensuring the lowest overall cost to reach emission reduction targets. An estimated MACC for Australia for the year 2020 is shown in Figure 14. Although most options are less expensive than CCS (CCS is the option just to the right of the break-even point represented by a green circle with the number 20), if deep emissions reduction targets are to be met then increasingly expensive alternatives will be pursued to the point where CCS becomes competitive (Mckinsey & Company 2008). However, this MACC may change significantly as technologies improve and costs decrease, so that by 2050 CCS could be a much more attractive option.

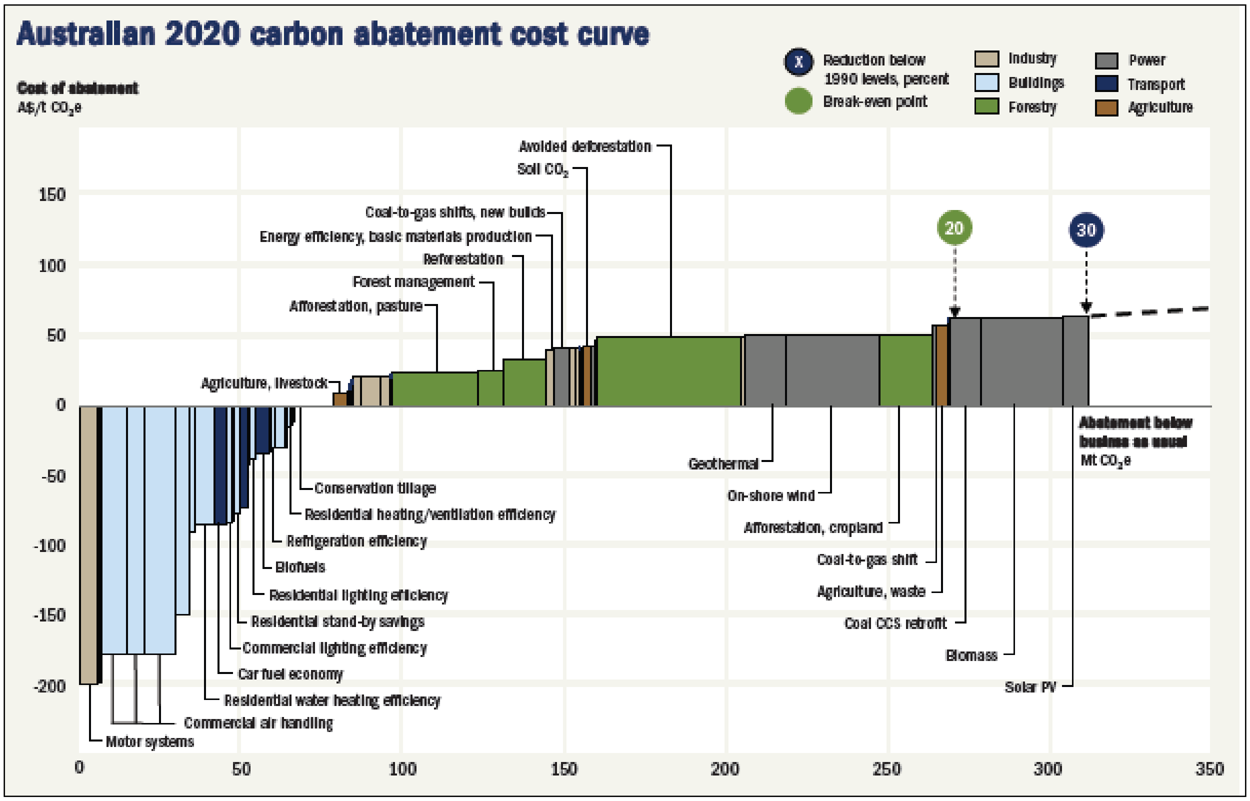

Figure 14 Estimated Marginal Abatement curve for climate change mitigation options in Australia for the year 2020 (McKinsey & Company, 2008)

2.3.6 CCS Risks

There are many potential risks associated with CCS that are of concern to the natural and built environment, as well as social and economic risks. This section will primarily address biological, chemical and physical risks. Experts believe that with proper care, these risks can be managed and lowered sufficiently to warrant the widespread use of CCS (IPCC, 2005). However, many of the studies on CCS risks are: outdated; not adequately modeled; do not account for different technologies or regional differences; and do not properly incorporate sensitivity analysis (Global CCS Institute, 2009). CO_2 leakage is the primary concern for CCS from an engineering perspective and can have wide-ranging impacts. The main risks for CO_2 capture, transport and storage are described below, with an emphasis on potential CO_2 leakage at any of these stages.

The capture portion of CCS is fairly risk-free from an environmental and health perspective. The main environmental and health concerns involve the small concentrations of chemicals such as H_2S and carbon monoxide (CO) in the flue gases of fossil-fuelled power plants. If these were to escape during the CO_2 capture process they could potentially harm nearby people, flora and fauna, although their concentrations are unlikely to be high enough to do significant damage. The concentrations of most of these chemicals would be comparable to power plants without CCS, although when the energy penalty is included they may be slightly higher (IPCC, 2005). The major CO_2 capture risks are instead related to its effectiveness at capturing CO_2, its potentially large costs and the effect of the consequent energy penalty.

Research into CO_2 transportation risks has looked at natural gas transportation as a model to emulate and improve upon. The majority of captured CO_2 has, and will continue to be, transported by pipelines for which stringent regulations on construction and operation are already in place. Furthermore, a safety plan and monitoring and emergency response measures are usually required for each pipeline project (IPCC, 2005). The incidents of pipeline failure are very low and continue to decline; in 1972 the rate of failure was 0.001/km/year and in 2002 the failure rate was 0.0002/km/year, both for small diameter and short distance pipelines in North America and Europe (European Gas Pipeline Incident Data Group, 2002). The failure rate of larger diameter and longer distance pipelines is even lower with an incident rate of 0.00005/km/year. Marine pipelines also have a very low incidence of failure (European Gas Pipeline Incident Data Group, 2002). Deep injection wells, however, may have a higher incidence of failure (leakage) (Suzuki, 2012).

The environmental and health risks from a CO_2 leak during transportation are likely to be minimal. Although there is no risk that CO_2 will ignite (unlike natural gas), there is still the possibility of fatalities due to asphyxiation from high concentrations of CO_2 and ecological damage from resulting increases in water acidity (IPCC, 2005). There is currently a knowledge gap on all of the ecological impacts of CO_2 released underwater. There will be complex interactions with atmospheric gases and CO_2 at the site of a pipeline or ship containment rupture due to the density and low pressure of compressed CO_2 (IPCC, 2005).

While there are many natural analogues of non-anthropogenic CO_2 being stored throughout the world, there are some important differences between natural and anthropogenic CO_2 storage. Natural sites have slowly accumulated CO_2 over thousands to millions of years so that CO_2 has gradually displaced the fluids in the reservoir as CO_2 migrates upwards. Displacing these fluids is a slow process, thus it does not significantly increase the pressure on the surrounding area. Natural analogues also show that some sites have appreciable leakage (although isotopic and carbon dating studies have shown that some sites of over 65 million years still show no leakage), indicating that even if sites do accumulate CO_2, they may not be perfect at containing CO_2 if injected at too high a rate (Stevens *et al.,* 2001). Anthropogenic CO_2 must be injected on a much shorter time span (and thus at a higher pressure) in order to be an effective climate change mitigation strategy. Care must be taken then to ensure that pressures do not increase to a high enough degree that faults are created, resulting in the release of CO_2. A schematic of potential leakage pathways is shown in Figure 15.

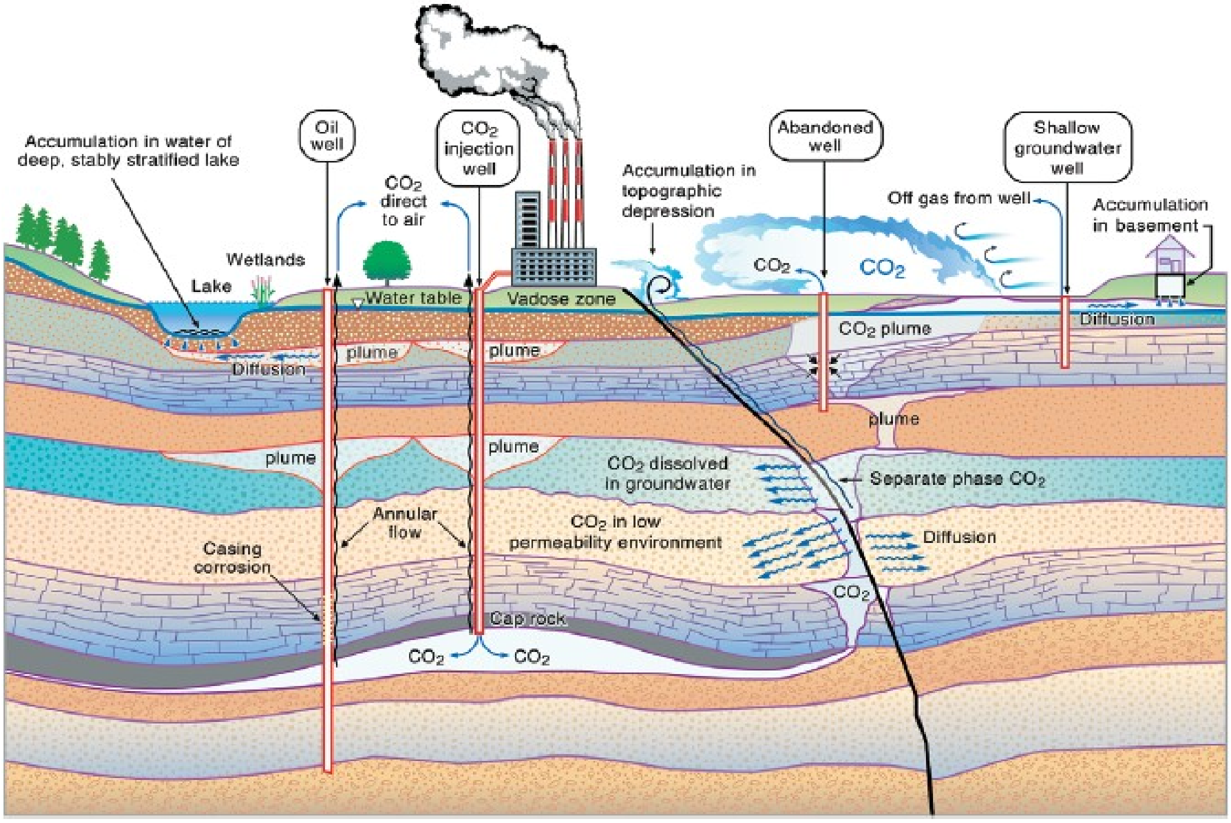

Figure 15 Sources of potential CO_2 leakage from geological storage (Zhang *et al.,* 2004)

Groundwater is important both to humans, for irrigation and drinking water, and for most plants and animals. Elevated CO_2 concentrations from subsurface leakage can contaminate groundwater, having lethal effects on plants and animals (IPCC, 2005). Soils and water can become acidic due to increased CO_2 concentrations. The increased acidity can mobilize chemicals such as arsenic, lead, sulphate and chloride, which will harm nearby biota. Oxygen and saline waters can also be displaced by incoming CO_2 (IPCC, 2005). These brines can contaminate aquifers, thus rendering the water useless to plants and animals or even harmful if the salt concentrations are sufficiently high. Monitoring can also prevent major leaks by quickly identifying problems. There are methods for extracting CO_2 from an area where there is a subsurface leak if it is detected early enough, however these methods tend to be expensive, thus adding to the economic risks of CCS. Impacts can be determined by collecting groundwater samples and analyzing them for major ions and pH levels. Tracers also allow for the flow and volume of groundwater movement to be monitored (IPCC, 2005).

Experience in EOR has shown that if proper sites are chosen for CO_2 storage, groundwater contamination is very unlikely to occur. The many wells (both production and test wells) used in oil and EOR drilling do, however, pose a risk to CO_2 storage as they increase the opportunity for CO_2 to escape if they are improperly sealed. Standards for plugging wells after drilling has finished have changed drastically over the past 100 years so that recently plugged wells have a very low chance of leakage, although large-scale disasters can still occur (The New York Times, 2010). Older wells, however, were often only plugged with mud and would need to be resealed in order to ensure CO_2 does not migrate through them (IPCC, 2005). Over time, especially on the timescale of thousands of years, well integrity is a serious issue for permanent CO_2 storage, with great uncertainty remaining.

CO_2 is more buoyant than most gases and liquids at depths of hundreds of metres below the surface and will move upwards if there are pathways available. Once CO_2 reaches the vadose zone (shallow subsurface soils), it is denser than air and may remain there under certain conditions. If subsurface leakage occurs, CO_2 will eventually collect in the vadose zone until it is dispersed by winds (if it reaches the surface) or slowly by diffusion (IPCC, 2005). If the leakage rate is high or dispersing mechanisms are slow, potentially dangerous concentrations of CO_2 can accumulate near the surface in low-lying areas. Concentrations of CO_2 greater than 7-

10% by volume, compared with concentrations of approximately 0.03% for normal ground-level air, pose a serious risk to human health due to asphyxiation. Animals and plants that are closer to the ground are also more likely to be affected by high CO_2 concentrations, since wind and turbulence increase with elevation which can dissipate the gas (IPCC, 2005). Situations with minimal wind can be dangerous if CO_2 does leak as these dissipating factors will not be present, and the CO_2 may linger long enough to cause serious health damage to plants, animals and humans.

In 1986, natural seepage of CO_2 from a volcano caused Lake Nyos in Cameroon to become fully saturated with CO_2 and to abruptly release over 2 Mt of CO_2 overnight. This seepage occurred in an area of a natural depression, which allowed the CO_2 to accumulate around human habitation killing over 1,700 people and thousands of livestock (Kling *et al.,* 1987). Although a massive CO_2 leak is a possible concern from CCS operations, it is not likely to occur in properly sited and monitored injection sites. A CO_2 build-up near an injection site would be detected well before concentrations reached a lethal limit. Storage sites will need to be properly mapped and characterized to ensure that all old wells are plugged and CO_2 transport pathways do not lead to lakes or near settlements in case leakage does occur. Cataloguing, capping and monitoring drilled wells is difficult due to the very high number of wells near potential CO_2 storage reservoirs. In Alberta alone there are over 350,000 oil wells with more than 20,000 added each year (Gasda *et al.,* 2004) and some studies show that up to one in six deep wells show some signs of leakage (Suzuki, 2012). Nevertheless, companies considering CCS are assessing many storage locations for potential CO_2 storage.

CCS is a complex, large-scale climate change mitigation strategy. It has the potential to significantly reduce CO_2 emissions from large point sources such as coal power plants. CCS can therefore act as a bridging solution to anthropogenic climate change by enabling existing technology and infrastructure to continue to be used until more sustainable solutions are developed. CCS also has many potential drawbacks including high capital costs, public opposition, risks of CO_2 leakage, and environmental and health concerns. Addressing these risks is a difficult task and will benefit from the effective use of decision analysis tools, which is discussed in Chapter 3.

CHAPTER 3
MULTI-CRITERIA DECISION ANALYSIS: MAKING CCS DECISIONS

3.1 INTRODUCTION TO DECISION ANALYSIS

Decision makers (DMs) are faced with many types of decisions, many of which are straightforward. In the CCS context, DMs must choose between the different technologies, locations and implementation plans. With expensive projects like CCS, that impact large numbers of people, the potential consequences of such decisions can be significant. DMs will therefore benefit from assistance in making informed decisions on complex problems. The tools to assist DMs are referred to as decision support systems (DSS). Some DSSs provide a formal method based on systematic reasoning for making these difficult decisions (Cavallaro, 2009), whereas others provide less systematic and more ad hoc assessments. One set of DSS methods attempt to achieve an optimal[6] solution through maximizing the expected utility of a project (Samson, 1988).

Early energy planning decisions were mostly focused on modeling energy-economy relationships to achieve the lowest costs and predicting future energy demands (Pohekar and Ramachandran, 2004). Limitations in energy supply and a growing understanding of the environmental impacts of fossil-fuel based energy eventually engendered more research in renewable energy. The inclusion of environmental and social impacts in energy-supply decision analysis has added

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[6] An optimal solution occurs when there is no other option that will lead to a better outcome (DeGroot, 1970).

further dimensions to these decisions that have not been well addressed in the past. However, recent decision analyses on energy production options are incorporating these varied and complex life-cycle impacts to become more comprehensive and complete processes (Ramanathan, 2004).

Traditional decision assessment methods such as cost benefit analysis (CBA), which use only economic indicators, are not adequate to assess complex, multi-attribute energy decisions (Tsoutsos *et al.,* 2009). Due to the increasing complexity of decision making in the energy field, a wide variety of decision analysis methods have been developed. The success of a decision can be measured using one or more criteria.[7] However, it has been argued that there cannot be a truly optimal (perfect) solution unless only a single criterion is considered (Løken, 2007). With more than one criterion, there are typically tradeoffs that need to be made to achieve the optimal solution (Phillips and Bana e Costa, 2005). For example, in a scenario in which a DM is choosing between three cars, one car may be inexpensive, but another car may be the DM's favourite colour (see Table 4 for an example). Depending on how important each criterion is to the DM, car A may still be the "best" (though not the truly optimal or ideal) choice even though it is not the highest ranked option on each individual criterion.

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[7] This thesis will consider the term 'criteria' to also represent project attributes, thus they can be considered as a requirement but also as an attribute by which a project can be assessed.

Table 4 Decision analysis using car selection as an example. The best car (highest score) is dependent on how important the cost criterion is relative to the colour criterion for the DM

	Car A	Car B	Car C
Cost (score out of 10)	8	6	9
Colour (score out of 10)	5	6	2
Total score	13	12	11

When risks are added into the decision analysis, there is no guarantee that a decision will result in an optimal outcome. The inability to achieve optimal outcomes occurs in part because the data used in making decisions is based on estimates and best available information. Estimates inherently have a degree of uncertainty. For example, one project may have a higher mean expected cost than another project but also a higher-level of uncertainty. The project with a higher mean score may not be the preferred choice if the DM is concerned with its uncertainty. Even though only costs are being compared in this example, trade-offs may be needed for an optimal solution to be achieved, such as accepting a lower expected score in order to obtain a lesser variation in expected scores (and thus avoid the possibility of a very negative outcome). Utility curves and preference functions are other methods that are incorporated into some decision models, which thereby add increasing complexity, as discussed below.

There are four basic sources of difficulty involved in difficult or 'wicked'[8] problems: complexity, uncertainty, multiple objectives, and different DMs' perspectives. DSSs help with all of these types of difficulties (Clemen, 1996). Firstly, a high-level of complexity makes a project decision difficult due to the myriad variables and factors involved in making a decision.

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[8] Wicked problems refer to problems that are highly complex and resistant to resolution. They usually require comprehensive solutions involving multiple people or organizations (Rittel and Webber, 1973).

Secondly, uncertain future outcomes are problematic as there is potential for detrimental events to occur; however, the likelihood of these events occurring is often poorly known. However, when the likelihood of a negative event is known, it can be incorporated using risk assessments. DMs may be risk averse and avoid conditions where a project could fail catastrophically. Thirdly, multiple project objectives can also increase the difficulty of decision making as it is rare that the objectives are in harmony with each other. Objectives are often specified to maximize profits, or minimize costs (which could be economic, social, engineering or environmental). Contrasting objectives may result in trade-offs that reach the most efficient decision overall, but that sacrifice elements of each individual criterion (Clemen, 1996). Fourthly, there can be multiple DMs, each with a different view of what constitutes an ideal project and therefore each having different objectives. For example, there could be five criteria for comparing a set of mutually exclusive decisions, but one DM may consider only three of them as important, whereas another DM could weight them all as highly important. DMs will also likely disagree on some of the criterion values, and especially about the level of uncertainty of the project (Clemen, 1996). Disagreement amongst DMs occurs because people have different perspectives, biases or inherent preferences. When presented with the same data, people will use their past experiences and preferences to inform their decisions. DSSs simplify 'wicked' problems by providing a framework to determine preferences for the criteria, expose uncertainties and clarify trade-offs in objectives.

3.2 TYPES OF DECISION SUPPORT SYSTEMS

Just as there are many different types of decision problems, there are diverse approaches to evaluating multiple decision options, each with their own strengths and drawbacks. In order to demonstrate the appropriateness of multi-criteria decision analysis (MCDA) to complex energy decisions such as CCS, the following major approaches will be explored below: economic analyses, life cycle assessment (LCA), energy modelling/forecasting, decision/event trees, and sensitivity analysis using thresholds.

3.2.1 Economic Analyses

One of the most widely used economic methods for decision analysis is cost-benefit analysis (CBA). CBA is aimed at maximizing benefits of a project or decision while minimizing costs (Pohekar and Ramachandran, 2004). It can include methods that characterize the social, environmental and economic consequences of decisions based exclusively on monetary values (Munier, 2004). Non-monetary attributes of a project can be translated into monetary values and compared on an economic scale (Cavallaro, 2009). It is an effective and widely-used method due to its simplicity, but it depends on the (questionable) ability to convert all values into economic units.

One of the major drawbacks of CBA is that not all aspects of a study are easily translated into monetary terms. Costanza et al (1997) for instance, estimated the value of ecosystem services and found that it was approximately twice the amount of the global annual gross domestic product, indicating that one of the two measures isn't accurate. Social and environmental impacts are especially difficult to quantify, as there is often not a market for them and thus no simple conversion factor into economic units. Ethical issues also arise when trying to put a monetary value on biodiversity, human health and other basic human or environmental needs, which have intrinsic but often not economic value (Cavallaro, 2009). Economic benefits for environmental and social services are usually determined through a stakeholder's 'willingness to pay' and, conversely, costs are determined through a stakeholder's 'willingness to accept' a monetary compensation in lieu of something changed by a project (Munier, 2004). For example, a stakeholder might be asked how much they would accept in lieu of using the land where a new power plant is destined. Likewise, a stakeholder might be asked how much they would be willing to pay to reduce CO_2 emissions. Due to the lack of an economic market for these services and goods, such proxy values are sometimes used. However, willingness to pay and willingness to accept do not adequately address issues of ability to pay or take into account people's understanding of the value of environmental services. Authors have criticized CBA (Kelman, 1981), believing that it is not adequate to assess complex decisions such as those involving climate change. Indeed, CBA is not used to assess many climate change problems due to ethical concerns with the method relating to the use of discounting, which values the future less than the present (Morgan *et al.,* 1999). The use of discounting is appropriate for many industries that have probable growth trends for the foreseeable future. However, discounting human values or ecosystem services does not properly fit into this method and can result in discounting future ecosystem services (which do not have unlimited growth potential), or discounting future human lives to negligible amounts and thus to not value them at all.

One of the major issues encountered in economic analyses of projects is that the costs usually occur at different times (e.g. construction, operation, maintenance and replacement, and decommissioning). Discount rates are also often used to translate all the costs that occur throughout the project lifespan into a net present value; however there is debate regarding what discount rate is most appropriate. Projects often have different lifespans which impacts decisions regarding what assumptions to make when a project is finished (Munier, 2004). DMs can assume that an identical replacement unit (a power plant component for example) will be used again once the current one reaches its economic lifespan. Replacing units with identical versions can be overly simplistic, as improvements in component efficiency and cost generally occurs during large-scale project lifespans. Projects such as CCS, which rely on relatively new technology, can expect significant technological advances in new models, resulting in large cost uncertainties but lower costs overall. To reduce these uncertainties, models are needed to forecast how different technologies may develop.

Economic analyses provide valuable insight into decisions but are limited in their use for assessing complex problems that involve significant environmental and or social factors. As will be discussed below, MCDAs are able to overcome some of these problems by integrating economic analyses into broader analyses with additional criteria.

3.2.2 Life Cycle Assessment

LCA is a method for measuring all the inputs and outputs of a system or process over its entire lifespan from conception to decommissioning (and sometimes including post-disposal monitoring or remediation). This method is often used in environmental assessment projects and was first comprehensively used in 2007 for complex energy problems by Viebahn *et al.,* (Pehnt and Henkel, 2009). LCA can be an important part of large-scale energy assessments as its detailed results can be used as input data, along with other data, for a 'higher-level' analysis that include additional decision criteria. LCAs can assist the development of CCS by identifying environmental impacts at each stage of the process, thereby facilitating their reduction (Sathre *et al.,* 2011).

LCA methodologies have been formalized by the International Organization for Standardization (ISO) in their 14040 environmental management series of standards (2009a), (Finkbeiner *et al.,* 1998). LCA is meant to categorize different environmental impact criteria in order to compare multiple options. The four phases of an LCA (goal and scope, life cycle inventory, life cycle impact assessment, and interpretation) (Baumann and Tillman 2004) will be discussed briefly below.

The first step of any LCA is to define the goal and scope of the assessment (Pehnt and Henkel, 2009). The project scope needs to be outlined by defining the assessment boundaries and timeframe (Pehnt and Henkel, 2009). Although there may be agreed-upon criteria to assess standard or common projects, each assessment is unique. Criteria need to be clearly stated to avoid compatibility problems with data and units. It is much easier to assess the relevance of all criteria at the start of a project, and identify accepted units, rather than at the end of an assessment when data may no longer be available.

The second step in a LCA is the life cycle inventory (LCI), which is strongly linked to the impact assessment stage in step three. All the potential impacts (or parameters) within the system boundaries are first collated then assessed in these two steps to determine their relative importance to the DM in the analysis (Pehnt and Henkel, 2009). Table 5 show the impact categories (criteria) in a typical energy problem with a focus on environmental issues. Conducting a LCI involves cataloguing and organizing data into impact categories. The life cycle inventory and impact assessment stages require planning because the entire process from conception and production to disposal must be taken into account, which, for a power plant with CCS, may need to factor in several decades of operation.

Table 5 Impact Categories used in a LCA for energy projects (adapted from Pehnt and Henkel, 2009)

Impact category	**Relevant parameters**	**Characterisation factor**
Cumulative energy demand (CED)	Consumption of energetic resources	CED (fossil and nuclear)
Global warming	CO_2, CH_4, N_2O Halocarbons	GWP100, CO_2-equivalent
Summer smog	NOx, NMHC, CH_4	Ethene-equivalent
Eutrophication	NO_2, NH_3	PO_4^{3-}-equivalent
Acidification	SO_2, NO_x, NH_3, HCl, H_2S	SO_2-equivalent
Health impacts	PM10, PM2.5, soot, SO_2, NO_x CH_4, formaldehyde, benzene, B(a)P, PAH, arsenic, cadmium, dioxin, furan	Years of life lost (YOLL)

The fourth step involves interpreting the LCI and impact assessment, as well as giving recommendations. Since different impacts are not easily compared to each other when using differing units of measurement, there often cannot be a simple conclusion or score about what the best option is. The discussion in step four should outline the positive and negative implications of each option and give a qualified recommendation for the best course of action. LCAs are an effective tool for assessing decisions because it compares many diverse factors and requires the DM to evaluate the impact of the impact of those factors. LCAs can also be used to feed into more broad studies as input data.

3.2.3 Energy Modeling/Forecasting

Another way of assessing different energy-related options is to model several alternative projects over a set period of time to determine which option best meets a given criterion. Generally, models are used to assess two or more alternative scenarios; in this thesis, these alternatives refer to multiple CCS projects. For instance, the emission reduction potentials of the CCS projects could be assessed to determine which project reduces CO_2 emissions with the lowest cost. The mix of energy options that ‘best’ meets the specified criteria would be chosen. Choosing the ‘best’ energy mix is highly subjective as there are many ways to evaluate energy mixes. However, objectives and criteria that will be used to compare the outcomes should be set in advance, thus reducing the subjectivity of the analysis. One of the early and widely cited energy-mix modelling studies was conducted by Socolow and Pacala (2004), who calculated the optimal contribution of different options for reducing greenhouse gases in order to achieve a limit on emissions. Each CO_2 reduction option is referred to as a climate stabilization wedge (see Figure 16). Each wedge represents one technology's (or strategy's) impact on reducing CO_2 emissions below a forecasted amount (the uppermost line on Figure 16). Cumulatively, the strategies can achieve significant emission reductions, of which CCS is expected to play a major role.

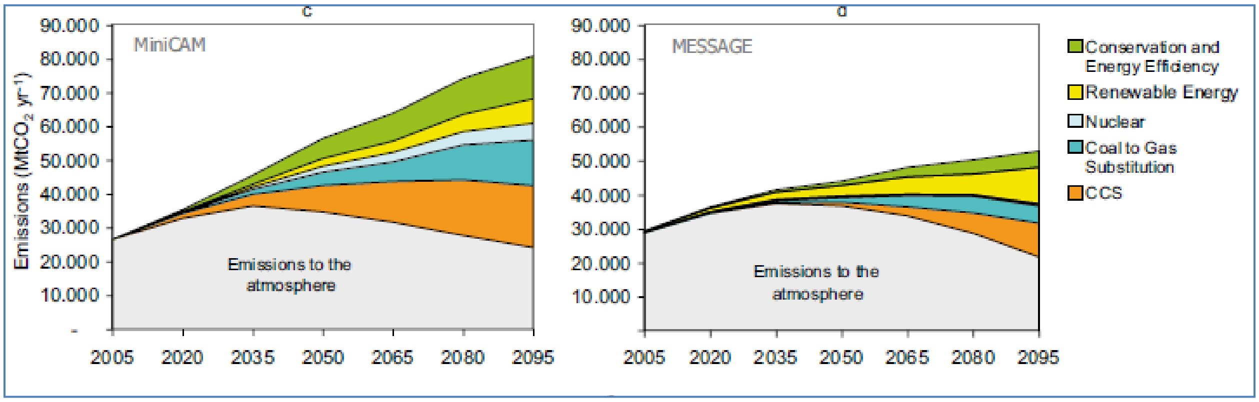

Figure 16 Potential for CCS to contribute to global carbon dioxide emission reductions. These energy models are used in the IPCC assessment reports and involve a more sophisticated stabilization technique than those first proposed by Pacala and Socolow. The differences between the two models (MiniCAM and MESSAGE) show that the uncertainty of the predictions is high (IPCC 2005).

The initial energy modelling studies were followed by more complex models assessing more options in greater detail. The calculations used in energy modeling are often very complex and rely on computer algorithms to combine several projections of energy demand. Energy modelling can be difficult because many of the factors used in the calculations are uncertain and interdependent, resulting in positive and negative feedback loops that are hard to estimate with a high degree of accuracy, particularly over a long time period. A trade-off is made where usually only a few key or high-level criteria are used in analyses, ignoring many other minor contributing factors due to their complexity and a lack of data. Using fewer input factors reduces the precision of the forecasts but is much easier to model. Energy modelling is an effective tool for assessing high-level, large-scale energy problems.

3.2.4 Decision Trees

Decision trees are used to visually display options for DMs (see Figure 17). Decision trees illustrate each of the choices that could be made at various points in time in a decision problem. The different decision options have estimated values assigned to them using best available data and expert opinion. They are referred to as ‘trees’ when displayed as a diagram as each decision follows a linear path and expands at each option, resembling the branches on a tree. The values of each decision are summed sequentially along the branches so that each final branch node has a total value assigned to it. The values at each decision node will represent the results of one-time decisions, whereas the final consequence or event node at the end of the branches will represent the cumulative values of each decision along the branch. The branch with the ‘best’ overall cumulative end value is then the option to choose as it represents the optimal combination of choices. Similarly, MCDAs can evaluate many alternatives by incorporating decision trees into the analyses.

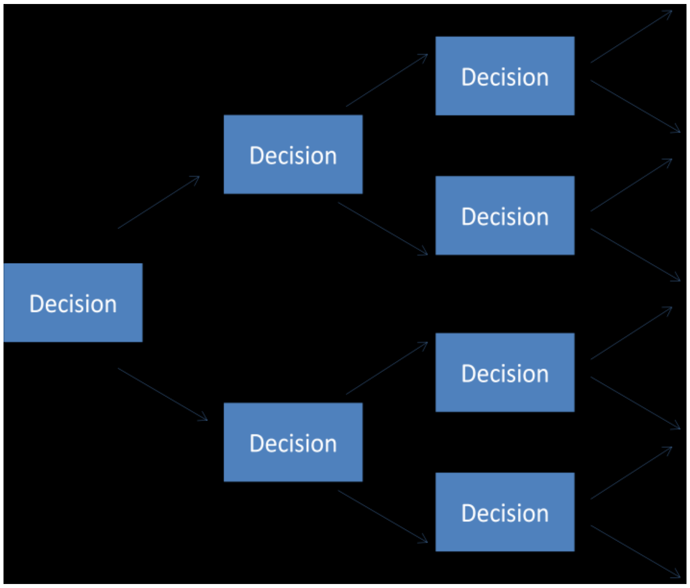

Figure 17 Sample decision tree. The increasing number of decisions resembles the shape of a tree as the decision tree expands

3.2.5 Multi-Criteria Decision Analysis

Multi-criteria decision analysis (MCDA) (or multi-criteria decision making) has become a popular method for assessing complex problems and is increasingly used for assessing energy options such as CCS (Wang *et al.*, 2009). The process is similar to that in LCAs in that it also assesses many criteria. A flowchart is shown in Figure 18 for a typical MCDA process and the general procedure is outlined in Section 3.5.1 below. The individual steps used in this thesis are described in more detail in Chapters 5 and 6. The CCS MDCA risk model developed in this thesis incorporates aspects of LCAs and builds upon the method by placing emphasis on amalgamating and weighting many heterogeneous criteria in order to provide DM-specific recommendations. MCDAs use data, such as those collected in LCAs, and apply DMs' weightings to determine which project best meets the DMs' specific preferences. MCDAs compare criteria on a common scale using user-inputted weights to show the relative importance of the criteria to the DMs. MCDAs can also use elements of CBAs but differ in that they evaluate decisions using qualitative and quantitative criteria that are not necessarily expressed on an economic basis (Cavallaro, 2009). MCDAs can easily incorporate socially- and environmentally-focused criteria, which may not be quantifiable due to their intrinsic values and ethical concerns, alongside strictly quantitative economic or engineering criteria by using a common unit of measurement such as utility or preferences. Therefore, MCDAs overcome some of the limitations of both LCAs and CBAs. There are several types of MCDA methods, including: value measurement models, goal, aspiration and reference level models, and outranking models (Løken, 2007), all of which are described in Appendix 2A. As MCDA is a general decision analysis framework, it is able to incorporate aspects of other methods such as LCAs, CBAs, sensitivity analysis and risk (discussed below) into a comprehensive decision assessment to suit the needs of the decision problem.

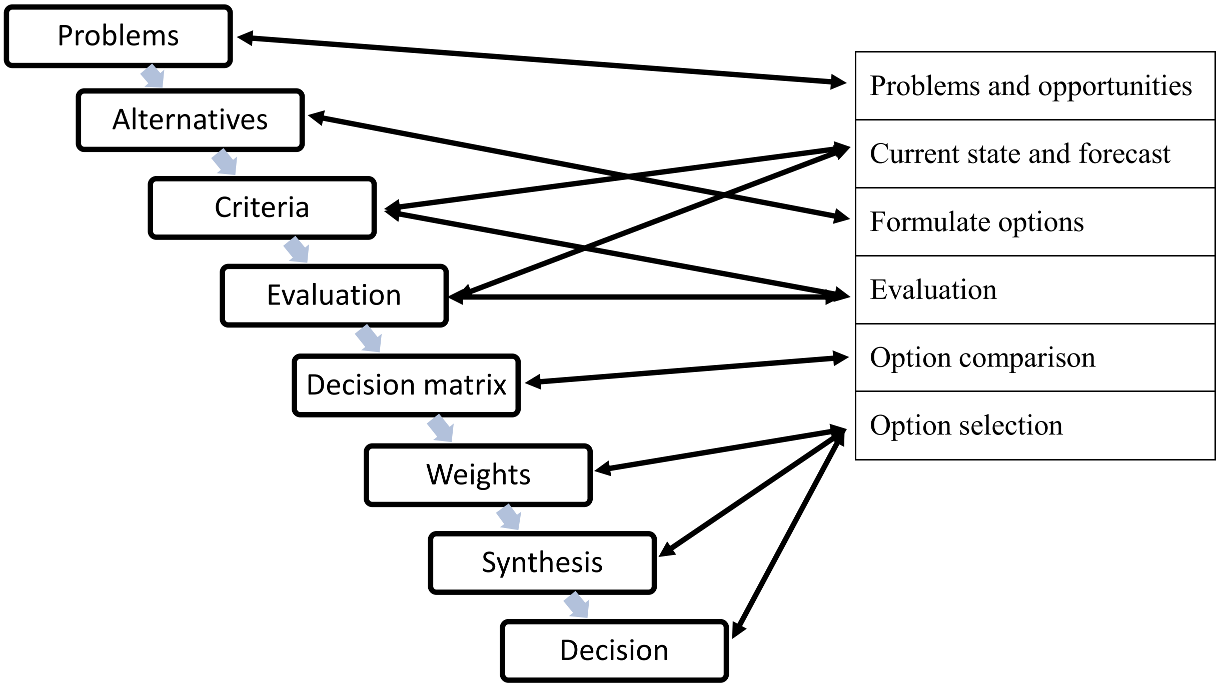

Figure 18 A planning process flowchart (left) combined with a multi-criteria decision support framework (right). This figure shows the relation between a planning process and a multi-criteria decision support framework (adapted from Cavallaro, 2009)

It is important to distinguish between a criterion and a constraint as they are often misunderstood. Constraints are the requirements that must be met for a project to proceed (Ramanathan, 2004), whereas criteria are parameters or attributes by which the success of a project can be evaluated. Criteria can, however, have thresholds or constraints beyond which the project may be infeasible. Criteria can also be described as "parameters used to evaluate the contribution of a project to meet the required objective" (Munier, 2004). This thesis will consider the term 'criteria' to also represent project attributes and factors as measures by which projects are assessed.

3.3 SENSITIVITY ANALYSIS AND THRESHOLDS

Sensitivity analysis is essential for any thorough decision analysis involving uncertainty. Sensitivity analysis is the process of varying the values of different inputs in a DSS by their expected range of uncertainty to determine how each input's variation affects the decision, and hence the viability of a project. Sensitivity analysis is not a precise science and will vary across projects (Clemen, 1996). The possible degree of variation for each criterion value is set by the DMs and assessment modellers based on the variability of the expected values. There are many types of sensitivity analyses and software programs that help DMs manipulate the variables and examine their impact on the consequences of a project (Clemen, 1996). Sensitivity analyses are performed as part of decision analyses in order to take uncertainty into account. Threshold values can also be used to measure when and how often a score on a criterion exceeds a prescribed limit (Munier, 2004). Thresholds often relate to standards, which when exceeded, may result in strong negative effects such as a project becoming unacceptable. An example could be a concentration of a pollutant exceeding certain legislated health limits, or a minimum CO_2 storage reservoir volume below which an installation is not economically viable. For example, a threshold of 23 Mt of CO_2 could be set as the minimum CO_2 storage reservoir volume required for a project to be acceptable (see Figure 19). In this example, a probability density function is used to represent an uncertain CO_2 storage potential. There is a 15% probability that this reservoir will have a storage volume below 23 Mt of CO_2. A DM could then decide whether they can accept the 15% possibility of the storage potential being less than this threshold. Other thresholds may be harder to quantify and may not be possible to assess at early stages in an assessment.

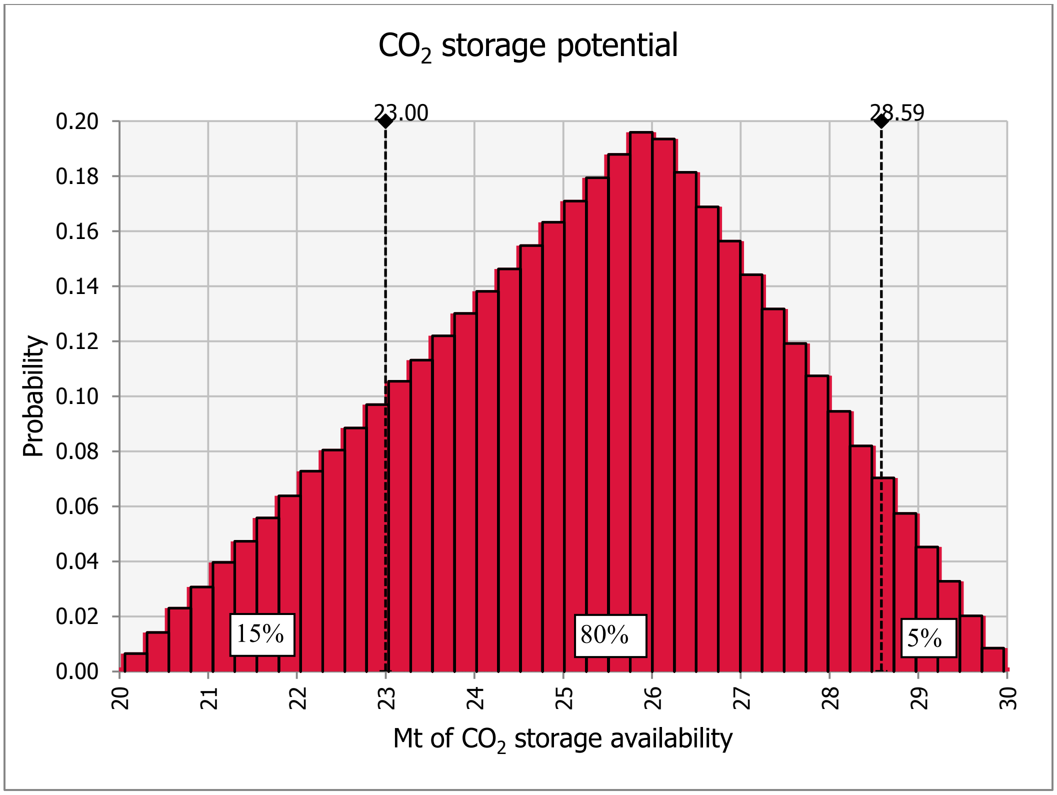

Figure 19 CO_2 storage potential for a project showing a minimum threshold of 23 Mt. In this example there is a 15% chance of the reservoir having a storage volume below this threshold.

One-way sensitivity analysis is the most basic type of sensitivity analysis. The analysis involves varying a single variable at a time in order to determine how large an impact it has on the project score (Clemen, 1996). Tornado diagrams can be used to display one-way sensitivity analyses for many variables on one graph. The variables are plotted as bars on a graph in which the horizontal axis represents the degree of impact on the final score (value of each alternative for the entire model) for a change in any input variable. The amount that the variable is changed by is usually a preset quantity such as 10% above and below the mean or a certain number of standard deviations from the mean. The longer the horizontal bar, the larger the impact is on the final score of the project (both positive and negative) (Clemen, 1996). The variables are plotted so that those with the largest range of impact are on top, yielding a tornado-like chart (see Figure 20 for an example of a tornado diagram). The diagram allows for a quick comparison of the impacts of individual variables. In this figure we see that public perception has the largest influence on the project score. Public perception may have a large impact on a project's viability due to perceptions of risk of CCS projects that are often influenced by analogous technologies such as nuclear and gas power plants, even though these latter do not engender the same risks. A DM could use the outputs of a tornado diagram to better understand which criteria have the largest impact on the expected project outcome and then research the underlying causes.

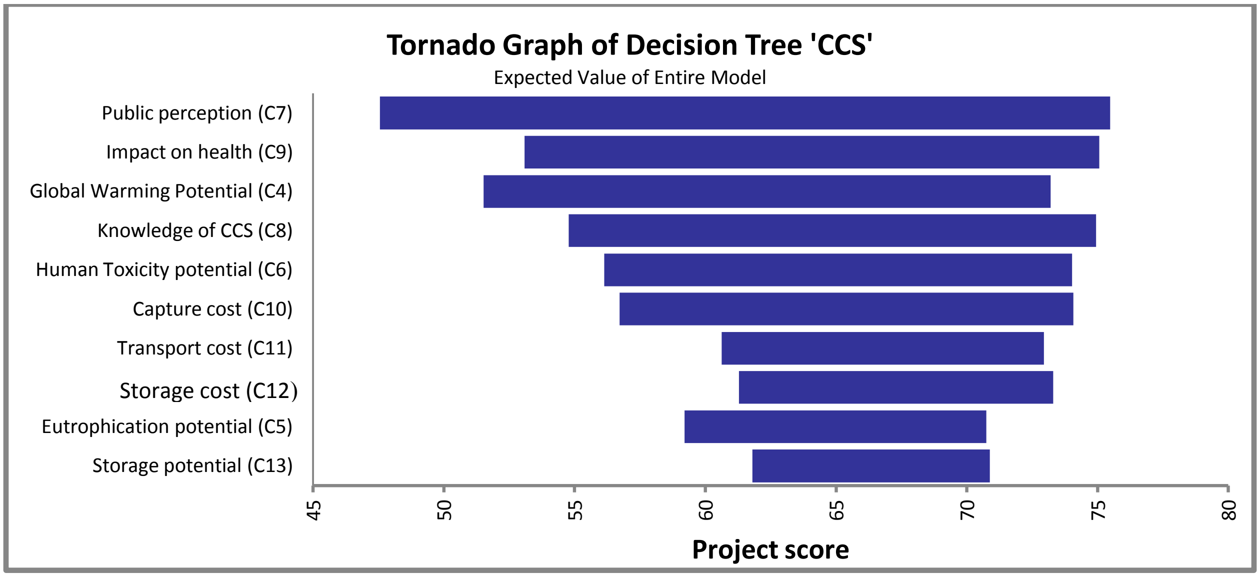

Figure 20 Tornado graph of the different energy production options created using Precision Tree. Lower cost project outcomes are on the right of the graph (i.e. higher scores)

3.4 RISK ANALYSIS

The term risk is often expressed in terms of the likelihood of events occurring combined with their associated consequences (ISO, 2009b). Risk has also been defined as a "state of uncertainty where some of the possibilities involve a loss" (Hubbard, 2009). Risk analysis is a method used to determine and assess this combination of a negative consequence and its probability of occurrence. Without such inherent uncertainty, a decision analysis would be much more straightforward, letting a DM choose the weighted optimal alternative. The uncertainty of an event is often expressed in standard deviations around the expected mean of a risk event (Munier, 2004). The major relevant sources of risk, and tools used to assess risk, are described below.

3.4.1 Types and Sources of CCS Risk

There are many types of risks relevant to energy decisions. There may be environmental risks, which include, but are not limited to: emissions of materials that have a negative impact on humans or the environment, and natural hazards such as earthquakes or flooding (International Atomic Energy Agency, 1998). There are other types of risks, however, that are less visible. These include less tangible risks such as economic risk – the risk that a project may fail, go over-budget, or take longer than expected. All these risks are a result of uncertainty; we cannot accurately predict the future so we must make choices based on the option that is expected to result in the best solution. There are no accepted standard categories of risk impacts, in part due to the wide array of possible risks in any domain. The steps involved in a sample health and environmental risk assessment for nuclear energy are shown in Figure 21 (see also Chapter 2 section 2.3.6).

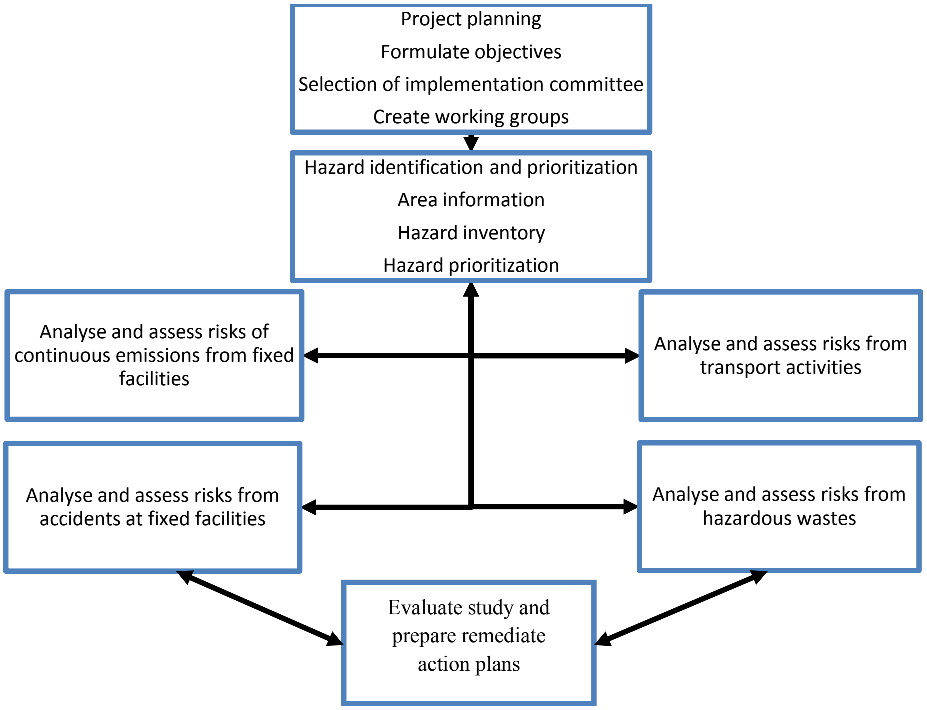

Figure 21 Methods and procedures for health and risk assessment (adapted from International Atomic Energy Agency, 1998)

3.4.2 Group Decision Analysis

Decision analysis for large-scale, difficult problems rarely involves only one person but more commonly includes several people who analyse and make decisions with the input of many stakeholders (Ramanathan, 2004). Group decision analysis can be advantageous as it incorporates experts from different fields, increasing overall creativeness, knowledge and understanding of a project (Mianabadi and Afshar, 2009). Most DSSs allow for the transparent and systematic input from various stakeholders. This can be done through weighted decisions, where stakeholders can input their preferences. Transparent and systematic decision analysis allows DMs to show stakeholders how they made their decisions and how various stakeholders were included. A transparent decision analysis increases DMs' confidence in models by avoiding 'black box' models where the process by which a decision was made is not understood or trusted and thus not used (Phillips and Bana e Costa, 2005).

Although it is ideal for all DMs to all agree on the best option, more often than not different preferences will lead to disagreement. Most DSS methods provide special procedures to determine which alternative is most preferred by the group as a whole (Ramanathan, 2004). The methods can be divided into two groups: those that aggregate the DMs' choices through mathematical equations and those that attempt to encourage DMs to modify their opinions to achieve a consensus (Mianabadi and Afshar, 2009). The use of 'fuzzy logic' is very beneficial to achieving group decision making as it allows for different opinions to be grouped together into similar preference intervals even if the values are not exactly the same (Subsorn *et al.,* 2008). Fuzzy logic incorporates the confidence of each DM in their opinions into the decision analysis by using a weighting system. In all aggregate group decision analyses, the relative standing or authority of each DM or stakeholder must be determined. A hierarchical group structure is often used in which one person is in charge who decides how much each person's opinion contributes to the final aggregated or consensus score.

3.4.3 Utility

Utility is used as a measure of the usefulness of an item, or of how much service it provides to a person. It can be measured by preferences between different choices. When comparing different alternatives, it is important to use the same scale for all criteria, such as 'utility units' (Clemen, 1996). A criterion such as the CO_2 emissions from a power plant can be converted into utility units by assessing where its value fits on a DM's preference scale with ranges from the worst case outcome (usually a zero score) to a best case outcome (usually a score of one). This process provides context to the DM's preferences and gives a relative impact as measured by that criterion, and where it falls on them. Where a criterion's value lies on this utility scale is subjective and is specific to the person who rates the criterion. This subjectivity is a drawback of using utilities, as a utility score must be made for each DM (or in collaboration in a group setting), which can take a lot of time. However, the subjectivity of using utilities is also a strength of the tool as it better reflects the individual preferences of the DMs for whom the analysis is being conducted. Another benefit of utility is that it can be used to compare heterogeneous criteria with different units on comparable scales.

The procedure of eliciting utility involves asking a DM a set of questions about each criterion to determine their preferences for the values along a continuum of best to worst possible cases. Once a series of preference choices have been performed, a utility curve can be generated by fitting a curve through the DM's preference ratings. A standard mathematical function representing the curve can then be calculated. This enables a decision analyst to interpolate and extrapolate a DM's preferences at any possible point within the established range of outcomes.

A sample utility curve displaying increasing wealth as a function of utility is shown in Figure 22. The curve illustrates the diminishing returns on people's preferences that is a feature of many criteria. In this graph, we can see that as wealth increases the marginal gain (preference) for further wealth decreases. This phenomenon results in non-linear curves. For example the marginal increase in preference between being given \$100 versus \$200 is not the same as the difference between \$1,100 and \$1,200. An increase of \$100 at the much higher wealth level does not have the same benefit. Gradually a point is reached where an increase in money only minimally increases the utility to a user, who is thus referred to as risk-averse.

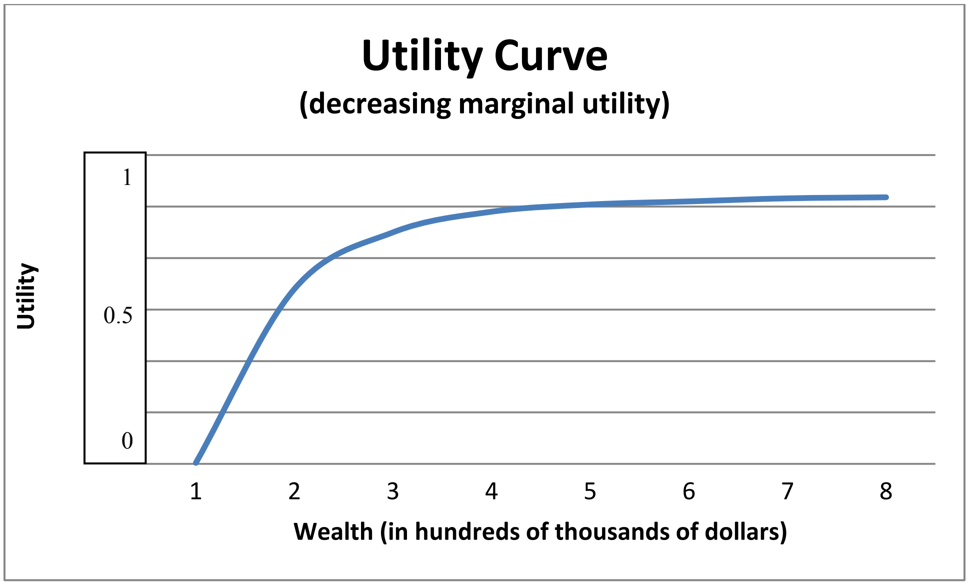

Figure 22 A utility curve as a function of increasing wealth showing decreasing marginal utility

The opposite situation to diminishing returns can also occur, which is shown in Figure 23 and is termed risk-seeking. In this case, each incremental increase in the value of the horizontal axis would increase the utility by proportionally more than the previous increase. An example of a non-linear increase in utility is the difference between being offered one movie ticket and being offered two tickets. The two tickets may be worth more than twice the utility of one ticket as it enables a friend to accompany you to see the movie, which can result in more than double the benefit of going alone. The literature often refers to non-linear utility relationships with regard to risk attitudes. An upward sloping, or convex curve, indicates that more wealth is preferred to less wealth at an increasing rate of change implying risk-seeking behaviour. A concave curve, or one that opens downwards, implies that the person is risk-averse (Clemen, 1996). By contrast with risk aversion, people would trade a gamble for a sure amount that is less than the expected outcome of the gamble. The risk aversion concept was first explored by Daniel Bernoulli and is expressed as the concept of diminishing marginal utility. This notion was formalized in the 1960s by Pratt (1964) and Arrow (1965) who used the elasticity of marginal utility as the standard measure of risk aversion (Eisenhauer, 2006). Risk-averse people tend to avoid situations where there is a positive expected outcome when there is also a possibility of a negative outcome. They therefore place more emphasis on the negative possible outcomes rather than the expected mean when making decisions.

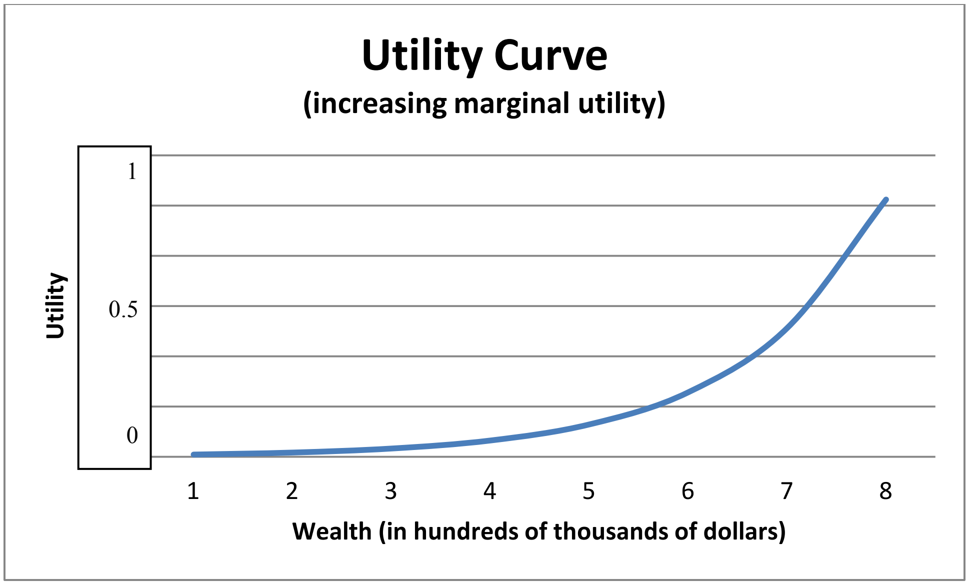

Figure 23 A utility curve as a function of increasing wealth showing increasing marginal utility

Utility curves are used in the risk model for CCS decisions to convert criteria into the same scale (see Chapters 5 and 6). This is done by DMs who provide relative preferences for the criteria values.

3.5 MCDA METHODS

The general goals of all MCDA methods are to help DMs with consistency and transparency and to increase decision analysis efficiency (Becalli *et al.,* 2003). There is, however, a wide variety of different methods that can be used to achieve these goals. To further complicate decision analysis, there can also be multiple objectives (sometimes competing objectives), as well as many criteria and alternatives. A single DM may even have multiple objectives such as maximizing profits while minimizing risks. Multiple DMs may have competing interests or objectives, such as minimizing environmental impacts versus maximizing job creation for a given endeavour.

3.5.1 Multi-Criteria Decision Analysis Process

Although the process of decision analysis can be straightforward and linear, the addition of further information as conditions change, through stakeholder feedback and additional data collection, may involve several iterations. Although MCDAs can refer to almost any decision analysis that includes multiple criteria, the main steps in a traditional MCDA include problem identification, objective formulation, selecting criteria and stakeholders, employing the decision method and evaluating the results. MCDAs are flexible so that the process can be adapted to any decision. An iterative MCDA process is described below and a sample decision analysis flowchart is shown in Figure 24.

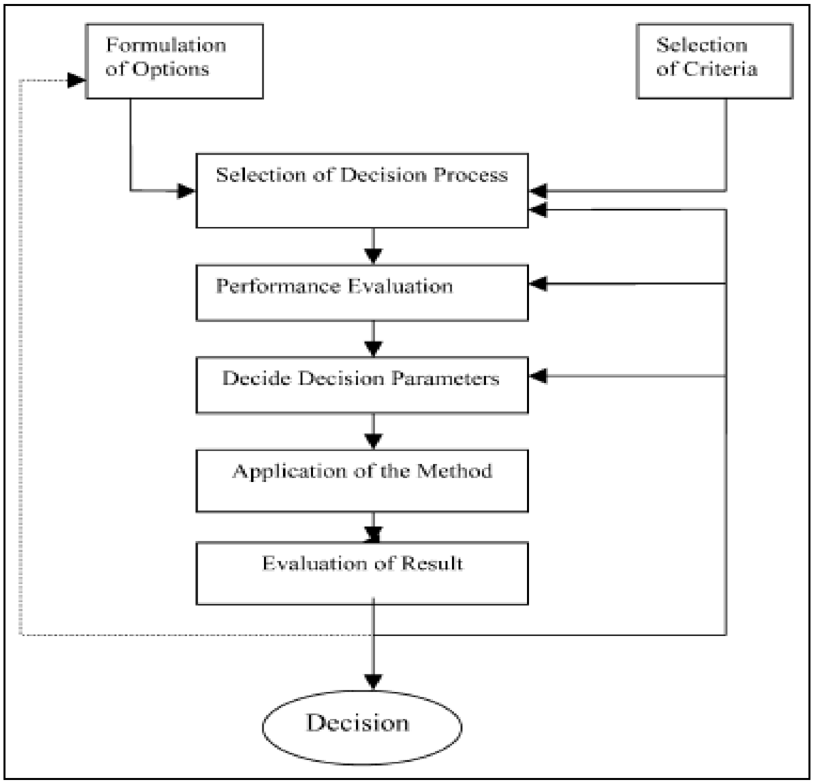

Figure 24 Decision analysis flowchart (Pohekar and Ramachandran, 2004)

The first step in the MCDA process is properly identifying the problem, followed by understanding the objectives of the situation. Formally determining objectives is a step that is often overlooked, as the problem is assumed to be obvious to DMs. This can lead to treating the wrong problem; an “error of the third kind” (Clemen, 1996). Selection of the decision process is the point at which the decision analysis method is chosen (e.g. Analytical Hierarchy Process, Tetra, ELECTRE, PROMETHEE, and others and described in Appendix 2A). The decision parameters are then determined and the process started. As new information is collected or conditions change, the process may be restarted, resulting in an iterative decision loop until the DMs are satisfied with the outcome.

Identifying who the stakeholders and DMs are in a project can be a very contentious issue, requiring a lot of care to be taken when deciding who may be impacted by a proposed project. A stakeholder is typically anyone who can be either impacted by a project, or can impact a project. Although that could result in thousands of people, usually only the stakeholders that have the largest impact on the project are included. Sometimes a lobby group or non-governmental organisation represents the interests of a particular segment of the public. Determining at what point to limit stakeholder involvement is addressed in this stage. Another method to limit the number of stakeholders involved in a project involves creating a geographical zone of influence around the project. Energy DMs often include high-level employees from utilities, politicians and other people who control aspects of the proposed project, (Ramanathan, 2004). A list of potential stakeholders and DMs for a CCS project is provided in Appendix 2B.

After defining the decision problem, the next step in the MCDA decision analysis procedure is the selection of criteria. DMs often do not include criteria that they think are unimportant. However, it may turn out that there are other criteria that are important to another stakeholder, thus 'unimportant criteria' (to some DMs) may still have a large effect on the final decision. Criteria should be considered carefully before excluding them from the MCDA process. Criteria identification should therefore be exhaustive and include all relevant stakeholders and DMs. Although not always possible, criteria should be mutually exclusive so that criteria are not counted twice within an analysis, which is discussed in more depth in Appendix 2A where analysis of factors is described. Careful consideration must be taken to ensure that all impacts are included in the decision analysis (see Appendix 2C for a list of the variables included in a sample CCS decision analysis). A list of impacts and criteria for a sample environmental decision analysis is shown in Table 6.

Table 6 Sample environmental impact and criteria checklist. The decision analysis is used to assess the impacts from a pollutant released into the atmosphere (adapted from Munier, 2004)

Impact type	**Yes**	**Extent of impact**	**Degree of mitigation**
Positive		There will be generation of employment in an industry with a higher multiplier effect	
Adverse	X	Produces air pollution with SO_2, NO_x and HS_2	With the new electrostatic filters the contamination will be just below the maximum thresholds, except for NO_x.
Primary	X	Affects human health	
Secondary	X	Produces acid rain	
Tertiary	X	Death of fishes in the river	
Measurable	X	It is very easy to take samples and to measure concentration	
Indeterminate			
Apparent			
Cumulative	X	On top of health hazard it will provoke acid rain, especially SO_2	
Able to be mitigated	X	Certain. Studies are conducted to determine the best system	
Residual impact			
Spatially related	X	Diffusion studies show a plume extending 25km from the plant site	
Temporal related			
Reversible			
Irreversible			
Likelihood	X	There is no doubt of the effects of this emission	
Unexpected impacts		Unknown	The construction of a higher stack could decrease unexpected impacts
Risk effects	X	There is some risk due to the nature of the gases released	Filters will be installed in the smokestack
Residual effects			
Population impact			
Interaction between impacts	X	Emissions could interact with another industrial plant releases	

There is no defined procedure for determining how many criteria should be included or where the boundaries of the analysis are. These are determined by the designers of the analysis along with stakeholders, and are specific to each problem. Although there is no prescribed method for determining criteria, the different criteria or variables can be generally divided into the following categories: technical, environmental, safety, social, economic, construction, spatial, political, and temporal, among others (Munier, 2004).

Baseline studies are needed for any thorough project analysis (Munier, 2004). Baseline studies enable DMs to understand the relative changes in different attributes, as they have an initial dataset against which to compare any changes during the study. For example, there may be a large change in absolute emissions of a criterion (e.g. CO_2), however if the concentrations are already extremely high, this may only be a small relative change. Baseline studies will also often reveal other criteria that may be impacted by the project and which could influence its viability.

Alternative projects or scenarios are evaluated based on their relative scores on the chosen criteria, as well as pre-determined thresholds. The goal is to first determine the non-inferior alternatives (Ramanathan, 2004). Non-inferior alternatives are also referred to as efficient, non-dominated or Pareto-optimal alternatives. The criteria screening process removes the obviously inferior alternative options from a decision analysis so that a more rigorous assessment can be performed on the remaining alternatives. To further reduce the number of alternatives, DMs can create thresholds or performance targets that the alternatives need to meet in order to be retained in the decision analysis process (Ramanathan, 2004).

Once criteria are determined and baseline studies completed (or in progress), values are assigned in a process termed ‘scoring’ (Munier, 2004). This score should reflect the DM’s opinion on how an alternative or option rates on a criterion (e.g. Project A has a score of \$5/tCO_2 for CO_2 transportation cost and a public perception of CCS score of 0.65 on a scale from 0-1). Some criteria will simply be quantitative, such as the emissions of a particular chemical, and require limited input from DMs. Other criteria may be more complex such as public perception, which could include input from public discussion meetings. The scoring process is intended to be as unbiased as possible using best available data and outside information including expert opinion. DMs are able to express their interests later in the process during criteria weighting, discussed below.

Criterion scoring has two steps; the magnitude (value of a project option on a specified criterion) and the importance of the criterion to the overall project score (Munier, 2004). The magnitude is simply how large the criterion value is. This could be a project’s impact measured by the concentration of a pollutant or the cost of a CO_2 capture component. The importance is how relevant the criterion is to the overall score of a project for a DM. For example, if the cost of a CO_2 capture component is miniscule compared to other criteria, then its importance may be low. DMs are usually asked to give a relative weight to each criterion representing their opinion of how important each criterion is to their project selection decision. Determining the project’s criterion value is usually done by direct measurement, such as surveying local residents, or by expert opinion and literature reviews. Many decisions are based on limited knowledge, so there is always an inherent uncertainty about how any project will actually score on a criterion. A database is usually developed in this step to organize the data and compare options.

Assigning weights to criteria is a vital step in the MCDA process because not all criteria are of equal importance to the overall score of a project. For instance, the overall cost of a project may be far more important to the DMs than the noise pollution caused by construction activities during the initial stages of the project. Criteria weighting allows DMs to indicate their preferences for how important a criterion is relative to another criterion (Ramanathan, 2004). The simplest weighting method is referred to as the simple multi-attribute rating technique (SMART). The ranking of alternatives using the SMART method is straightforward: DMs score each project on each criterion using a scale of 0 – 100. DMs then assign values to the remaining project's criteria relative to this initial value. The overall performance of the alternative is simply a summation of the criteria values multiplied by their weights (Ramanathan, 2004).

3.5.2 Benefits and Drawbacks of MCDA Methods

The MCDA method used in the CCS risk model for this thesis is based upon aspects of several common tools. The most common MCDA methods (AHP, PROMETHEE, ELECTRE GP, TOPSIS, STEM, MAUT and MAVT) are discussed below and in Appendix 2A. The field of MCDA has not yet reached a mature state and therefore there are problems with the methods currently used (Barzilai, 2008). Some problems are inherent to all methods whereas others are unique to specific methods. The benefits and drawbacks of the most popular methods are discussed below.

One pitfall of many MCDAs is that a wrong or inappropriate method can be used, resulting in precise information that is not accurate or that does not address the decision properly. This is more of a problem of identifying the proper method rather than a problem inherent to any of the models. Care must be taken to ensure that the appropriate method is used as not all methods can be applied universally to decision problems. If an inappropriate method is adopted, DMs may end up distrusting the end result or not understanding why certain options were ranked higher than others (Løken, 2007). Identifying the appropriate decision method is difficult as every decision is unique. An understanding of the benefits and drawbacks of the methods is therefore very important.

For more complex problems it has become commonplace to use a combination of methods to provide a better decision analysis (Løken, 2007). As discussed below, the MCDA risk model developed in this thesis draws upon elements of other models, but is developed independently so as to best address CCS-specific decisions. Using multiple decision analysis tools can build on the strengths of multiple models and cover for the faults of individual methods as well. Conversely, the drawbacks of the methods could combine to result in a poorer result overall. Some of the popular pairings used to build on the strengths of popular models for energy decision analysis are: AHP with PROMETHEE II, AHP with TOPSIS and AHP with GP. The AHP method is clearly very popular in combination with other methods (Løken, 2007). ELECTRE is also very useful as a first step in the analysis in order to derive a reduced set of feasible solutions, which could be shortlisted to undergo a more thorough analysis performed afterwards.

Many of the MCDA methods involve assigning a relative score for one criterion over another. Pair-wise comparisons are the most common example of relative scoring, in which criteria are valued based on their relative preference to each other. If done improperly, relative scoring can, however, result in meaningless values (Barzilai, 2008). For instance, measuring without units can create scales in which addition and multiplication are not applicable, such as when comparing preference for colours that do not have a natural zero on a utility scale. Relative scales can be problematic as the concept of zero utility or zero preference is not well defined. Nonsensical utility values can also be made such as "On a scale of 1-10, how far is Lisbon from Amsterdam?" (Barzilai, 2008). These preferences must be made in relation to other options so that there is a physical scale or alternative with which to compare. Relative scales may work for value judgements but do not work for all criteria. It is still unclear whether psychological properties (preferences) can even be measured empirically, as debate into the concept was dropped by the British Association for the Advancement of Science in 1940 without resolution and has not been discussed at length since (Barzilai, 2008).

Thresholds have been discussed in Section 3.3.5 and provide a unique problem for MCDA. Some MCDA programs allow for a criterion's distribution of scores to be entered, giving a range of possible values that provides a more comprehensive representation of a criterion's possible values. Using a criterion's distribution of potential scores would be similar to running a simulation a number of times at each value between the minimum and maximum distribution values (as is done with Monte Carlo simulations and sensitivity analysis which are explained in more depth in Chapter 5). However, using the expected value of a criterion, or even a distribution of expected values, does not necessarily make sense to decision-makers. People are often risk-averse and even if there is only a miniscule possibility of a negative event occurring, they may refuse to accept it (Barzilai, 2010b). In these cases, a threshold value can be used in which an alternative is excluded from analysis if it could exceed that value.

3.5.3 Multi-Criteria Decision Analysis for Energy Problems

Energy production can entail a wide variety of environmental, social, and economic impacts and risks. There is a growing worldwide awareness of these issues. It is now recognized that the identification, assessment and management of these risks is essential to project assessment (International Atomic Energy Agency, 1998). Increasingly complex MCDAs attempt to address these complex issues.

Energy decision analysis is an area that is often addressed with MCDA DSSs. MAUT and MAVT for instance are commonly used in choosing sites to locate power plants (Ramanathan, 2004). Because many decision problems, including energy-related problems, are now so complex, with many options and a large number of stakeholders, the decisions made are more often satisfactory, instead of ideal, due to compromises that must be made. Although energy decisions can be decomposed into smaller portions, such as determining the location of a plant or transmission type, most problems are interrelated and benefit from holistic assessments (Ramanathan, 2004). Energy problems often have another dimension of complexity in that they are highly dependent on supply and demand for electricity and materials. DMs therefore have to model and forecast these trends as well (Beccali *et al.,* 2003).

Even when comparing drastically different options, a project's scores on the criteria result in a mix of high and low ranked criteria, and rarely produce a dominant solution. With many different alternatives and many criteria, it would be rare if one alternative performed best in all categories. This has led to more complex decision analysis tools to aid in decisions in which trade-offs are required. Challenging facets of energy planning decisions include site selection, pollution control options and the input of multiple objectives from many different stakeholders (Clemen, 1996).

In part due to the complexity of these problems, a wide range of decision analysis tools have been developed. Guitouni and Martel (1998) argue that there is no one MCDA that is consistently better than another. They have found that in practice DMs are unable to justify why they choose one method over another other, and that this decision is often related solely to a familiarity with certain methods. A lack of understanding of decision tools leads to DMs attempting to fit decision scenarios to preferred MCDAs instead of the other way around (Guitouni and Martel, 1998).

MCDA methods are ideally suited for energy decisions due to the many sources of uncertainty, wide-ranging impacts, long time frames and high capital costs resulting in many trade-off decisions (Huang *et al.,* 1995; Løken, 2007). An energy decision case study from the peer-reviewed literature that further describes aspects of MCDA is provided in Appendix 2D.

As discussed above, there are many benefits and drawbacks to MCDA methods. More specifically, there are also gaps in the application of MCDA methods to energy decision making. Barzilai (2010a) argues that the mathematical models that are typically used in MCDA methods are unsuitable for representative decision analysis. The preferences behind these models are based on psychological attributes that cannot be measured accurately, or potentially at all. Preferences are also relatively transitory and often change over time, making them poor representations for long-term problems; a project's score can change simply by asking a DM the same questions on a different date or by giving them further information. Although proposing a whole new MCDA method is unrealistic, it may be more appropriate to use less complex and open models such as a simple decision tree instead of 'black box' approaches where the inner workings of a program are unknown or at least not well understood by the DMs using the tool (Figueira *et al.,* 2005). Decision analysis could then remain more of a guide instead of a solution, where DMs are aware of the limitations of the models and take them into account.

Decision analysis is a complex and varied field with many different methods aimed at improving decisions. There are drawbacks and benefits to all of the methods, including MCDA. MCDA, however, is better able to address the myriad of variables needed in complex energy decisions by incorporating aspects of many decision analysis tools used in other methods to meet to needs of specific decision problems.

CHAPTER 4

AN INTERDISCIPLINARY PERSPECTIVE ON CARBON CAPTURE AND STORAGE ASSESSMENT METHODS

The previous two chapters outlined the different aspects of CCS and decision analysis methods. This chapter provides an assessment of recent decision analysis methods used for assessing CCS. It reviews the interdisciplinarity of research into CCS in economic, social, environmental and engineering fields. It also provides recommendations for future studies to help avoid delays and cancellations in CCS projects. The paper has been submitted for publication to the Journal of Industrial Ecology. Dr. Ronald Pelot and Dr. Kate Sherren are co-authors on this article.

4.1 ABSTRACT

Climate change is one of the most serious threats facing humankind. Mitigating climate change will require a suite of actions to reduce greenhouse gas emissions. Carbon Capture and Storage (CCS) is a new technology aimed at mitigating climate change by capturing and storing carbon dioxide in deep geological reservoirs. CCS has risks characteristic of new technologies, as well as risks unique to this technology and its application. Large-scale CCS decision making is complex, encompassing environmental, social and economic considerations and requiring the risks to be taken into consideration. CCS projects have been cancelled due to inadequate assessments of risks. To date, studies assessing CCS have been limited mostly to environmental, social and economic fields in isolation from each other, predominantly using life cycle assessments (LCAs), cost benefit analyses (CBAs) or surveys of public perception. LCAs, CBAs, and surveys of public perception all have limitations for assessing difficult multi-faceted problems. Incompatibilities across CCS assessment methods have hindered the comparison of the results across these single-discipline studies and limited the possibility of drawing broader conclusions about CCS development. More standardization across assessment methods, study assumptions, functional units, and assessment criteria for CCS could be beneficial to the integration of multiple study results. We propose a set of criteria, which decision analysts could use to develop CCS-project-specific criteria lists in order to comprehensively assess a CCS project's viability. This list was created by determining the frequency of use of each criterion in recent studies, with a focus on their use across disciplines.

Keywords: Carbon capture and storage (CCS); life cycle assessment (LCA); cost benefit analysis (CBA), multi-criteria decision analysis (MCDA); gap analysis

4.2 INTRODUCTION

Climate change is considered by many to be the most serious threat facing the world today (Rackley 2010; Patz et al. 2005). Climate change is caused largely by anthropogenic emissions of greenhouse gases (GHGs). GHGs comprise many types of molecules of which carbon dioxide (CO_2) has the largest impact on anthropogenic climate change (Lashof and Ahuja 1990; IPCC 2007). GHGs accumulate in the atmosphere where they trap heat, leading to a warming of Earth's surface and changes to the climate (IPCC 2007). Limiting GHG emissions to a sufficiently low atmospheric concentration to prevent catastrophic climate change is an extremely complex and multi-faceted problem (Ludwig 2001). No one 'silver bullet' technology or action will prevent climate change; many measures will need to be pursued.

Carbon Capture and Storage (CCS) is a relatively new suite of technologies and methods aimed at mitigating climate change by capturing and storing CO_2 in deep geological reservoirs instead of releasing it into the atmosphere. The Intergovernmental Panel on Climate Change (IPCC) considers CCS to be one of several options needed in the "portfolio of mitigation actions for stabilization of atmospheric greenhouse gas concentrations" (IPCC 2005). CCS refers to a process and not a single technology, as there are many different technologies that can achieve these actions (Meadowcroft and Langhelle 2009). In general terms, CCS is the process of extracting CO_2 (typically from the flue-gas stream of a fossil fuel-fired power plant), compressing the gas into a supercritical state and transporting it to a geological storage site (Natural Resources Canada 2006). The compressed CO_2 is then injected into geological formations such as depleted oil and gas fields or subsurface saline formations. Typically, the

CO_2 remains in a supercritical fluid phase, though over time it may form solid carbonates through geochemical reactions. The injected CO_2 ought to remain stored under pressure in the geological formation, although there is a small possibility of leakage out of the reservoir. Over the last few decades the individual components of CCS (CO_2 capture, transport, and storage) have been successfully implemented in many commercial projects whose primary purpose is not CCS (Havercroft et al. 2011). CCS combines these individual components on a large scale, which creates new challenges such as economic viability and storage of large volumes of CO_2 underground. Several pilot and demonstration plants exist, but few large-scale commercial projects incorporating all three stages have been developed to date (MIT nd; IPCC 2005).

Decisions about whether to, or how best to, implement CCS are complex and should take into consideration environmental, social and economic impacts due to its long life-cycle, broad impacts and diverse stakeholders. Stakeholders include, but are not limited to: government agencies, power plant operators, local community groups and business, and environmental organizations. Some of the impacts of CCS can include increases of: local pollution, and water use, electricity prices, and decreases to property values, groundwater quality, and health due to CO_2 leakage. CCS development faces large risks as a result of its novelty, its uncertain safety, technological and storage reliability and the complexities that may arise during its application. Consequently, decision makers (DMs) such as government policy-makers and large energy companies have encountered difficulties implementing commercial CCS projects. When developing CCS projects, DMs must choose the CO_2 capture technology, transport method and storage implementation options, including the location, scale and timing of CO_2 storage, as well as the level of safety precautions and public engagement that should be adopted, among other considerations.

As CCS is a new methodology with far-reaching consequences, there are many hurdles that it must overcome in order for it to become widely accepted and adopted. For example, public opposition to perceived or actual risks, and high and uncertain costs can sideline or postpone CCS projects such as has occurred at Longannet in Scotland, Jaenschwalde in Germany, Barendrecht in the Netherlands (Carbon Capture Journal 2010; Reuters 2011; Terwel et al. 2012) or the Weyburn-Midale CCS-EOR research project in Saskatchewan, Canada where there is some local public opposition (Vanderklippe 2011). Other obstacles include uncertain revenue streams, changing regulatory regimes, and complex value-chains (Rai et al. 2009). There are parallels between the technologies used in, and obstacles facing, CCS and those associated with the oil extraction, SO_2 scrubbing, LNG and the power generation industry (Ramanathan 2004; Rai et al. 2009). As with these other large-scale technological projects, CCS decision analyses are becoming increasingly broad in scope due to their consideration of environmental and social factors, alongside economic ones (International Atomic Energy Agency, 1998; Ramanathan 2004; Wang et al. 2009). This broadening of scope has rendered CCS energy decisions even more complex.

Decision support systems (DSS) are tools that provide a formal framework to assess difficult problems in many fields including energy development and projects with large-scale environmental and social implications (Cavallaro 2009). A wide variety of DSSs exist for both detailed and high-level assessments. In high-level assessments, to be of use to decision makers, DSSs need to be able to transparently incorporate economic and non-economic factors, risk and uncertainty (Phillips and Bana e Costa 2005). Comprehensive and multi-disciplinary approaches are needed to fully assess high-level, complex problems (Härtel and Pearman 2010). Current studies assessing CCS, however, focus mainly on detailed, single disciplines using either life cycle assessments (LCAs), cost benefit analyses or social perception surveys in isolation. This large and growing body of single-discipline research on specific aspects of CCS provide the foundation for broad studies. However, such multi-disciplinary CCS studies, which combine elements from many fields, have so far been limited in use, in part due to the incompatible methodologies and parameter assumptions of the single-discipline source reports (Allinson et al. 2006).

This paper examines common methods currently used to evaluate CCS options through a review of the scholarly literature in the field. Specifically, we compare the criteria used within the various methods of assessment, and identify complementary indicators across disciplines. We then analyse which aspects of CCS are predominantly studied and which areas could benefit from further research. Finally, we outline a holistic multi-disciplinary approach using multi-criteria decision analysis (MCDA) which is recommended for future, high-level CCS decision making, including an initial proposed set of assessment criteria that encompasses social, economic, environmental and engineering aspects. This study builds upon work conducted by Allinson et al (2006), the IEAGHG (2010), and Markusson et al (2012), who have reviewed CCS assessments from an economic, environmental (LCA focus), and social perspective, respectively, by linking the three focus areas into a more holistic decision framework.

4.3 METHOD FOR COMPARING ARTICLES

We conducted a literature review of articles that assessed CCS in the social (e.g. surveys of public perceptions), environmental (e.g. LCAs), and economic fields (e.g. CBA and economic comparisons). Since the publication of the IPCC special report on CCS (2005), interest in climate change mitigation strategies has continued to increase, and many more CCS pilot and demonstration projects have been built. Subsequently, significantly more assessments of CCS have been conducted (CO2CRC, 2010; Meadowcroft and Langhelle 2009; Khesghi et al. 2012). Due to the rapidly changing field of CCS and technologies in general, this study only includes articles that were published between 2006 and June 2012 (Rubin et al. 2004; Rodemyer et al. 2005; Rubin et al. 2007). Forty one articles were included in this assessment, selected from the following publications: *International Journal of Greenhouse Gas Control; International Journal of Environmental Research and Public Health; Journal of Power and Energy; Environmental Progress; Renewable and Sustainable Energy Reviews; Energy Policy; Energy; Chemical Engineering & Technology; Journal of Industrial Ecology; Petroleum Science and Technology; Environmental Science and Technology; Risk Analysis; Biomass and Bioenergy; Energy Procedia; and Climatic Change*. To complement articles found during a broader research project, searches within the above journals were made using the following words: carbon capture and storage, CCS, and carbon sequestration, individually as well as in combination with: life cycle assessment, environmental assessment, economic assessment, cost benefit analysis, public perception, survey, interviews, life cycle impact assessment, price, cost, energy assessment, energy modeling, risk assessment, multi-criteria decision analysis, scenario analysis, energy integration, energy comparison. The analysis included only comprehensive studies, defined as studies that assessed CCS using multiple criteria. Studies that conducted an in-depth analysis of

CCS using only one criterion, and were thus not intended to inform broad, high-level decision making were not included in this analysis. Articles with a legal or engineering focus were not included in this analysis as their scope was limited to these single disciplines. In practice, we have found that legal, regulatory, and engineering factors function as minimum thresholds or barriers for CCS projects and not as criteria which projects are evaluated.

We grouped articles into three broad categories (environmental, social and economic) based on which category encompassed the majority of their criteria. While these three categories appear to cover the issues studied in the articles, we included CO_2 leakage as a separate fourth category. Although CO_2 leakage is not an assessment type or category on the same level as environmental, social or economic studies, it is included due to its importance to CCS performance and lack of consistent inclusion in the studies reviewed. A CO_2 leak is of significant concern for CCS implementation as it can impact all other three categories. Articles were also categorized by the type of assessment used or area of focus: economic assessments (which used CBA as the predominant assessment tool), LCA, risk assessment, surveys of public perception, scenario analysis, and energy integration/comparison. We noted the number of criteria included in each study and how many categories were spanned.

The next step in our analysis involved calculating the number of criteria used in the studies. If a study mentioned a criterion, but did not explicitly state that it formed part of their analysis, then we did not ascribe that criterion to that article. For example, many studies mentioned issues such as CO_2 leakage and capital cost but did not include them in their analysis. We filtered out the important criteria by frequency of use across the publications. Criteria that were only used in one or two studies were not included, such as ‘external benefit’ and ‘external cost’. In keeping with our high-level, multi-disciplinary perspective, very similar criteria were aggregated. For example, for the economically-focused studies, the study criteria presented were reduced from 13 to 9, acknowledging that some similar terms were referred to by different names, although they broadly assessed the same factor. ‘Total cost’ was therefore combined with ‘capital cost’ and, similarly, ‘Operating costs (OPEX)’ was combined with ‘variable operating costs’. Due to the wide variety of criteria and their overlapping nature in environmentally-focused assessments, several of the environmental criteria were also combined. Criteria in studies focusing on social aspects of CCS were much more difficult to categorize and compare than those in the economic and environmental studies. This difficulty was largely due to the wide variety of questions posed in surveys, interviews and focus groups, as they could be phrased slightly differently while attempting to assess the same criterion. The social studies typically asked several dozen questions of respondents, but these were grouped into the 9 categories shown in Table 7 for this review.

Table 7 Sample of questions and statements from social assessment studies of CCS

Question topic	Criteria category
Perceived likeliness of risk for the environment	Perceived impact on climate change
Perceived impact on climate change	
Perceived likeliness of risk for personal safety	Perceived health impact
Perceived likeliness of risk for offspring	
Cost of CCS relative to other technologies	Perceived cost
Impact of CCS on electricity prices	
Relative preferences between climate mitigation technologies	Impact on other technologies
Perceived risk of CO_2 leakage	Perceived leakage
Perceived likeliness of risk of being inconvenienced	Public perception/acceptance of CCS
Opinion of CCS	
Knowledge of CCS	Knowledge of CCS
Perceived economic benefit for local communities	Perceived benefit
Perceived pollution reduction	
Trust in industry on CCS issues	Trust in experts
Trust in environmental non-governmental organizations on CCS	
Trust in government on CCS issues	

4.4 ASSESSMENT OF CCS ARTICLES

Of the forty-one articles reviewed, 11 had an economic focus, 12 were about social implications and 18 assessed environmental impacts (see Table 8). Five of these articles also explicitly included CO_2 leakage, displayed in the fourth last column from the right. The articles were assessed from a quantitative perspective, from an interdisciplinary research perspective and within each category type.

Table 8 Criteria used in studies. Each row represents an individual study. Each column lists a criterion that recurs throughout the 41 articles. An area cell is highlighted when a study included the criterion listed in that column. Criteria are grouped and coded by colour: green represents environmentally-focused criteria, blue represents social-oriented criteria, and red represents economic-based criteria. The number of criteria assessed in each study is tallied in a column towards the right of the table. The studies are also coded in yellow in the last set of columns to show the type of methods used.

Article	Criteria																													# of criteria	# of categories	Method					
	Environmental										Social									Economic									CO$_2$ leakage								
	GWP/ CO$_2$ emissions	Acidification	Eutrophication	Ozone/ air quality	Human toxicity potential	Resource use/ energy demand	Aquatic ecotoxicity	Ecotoxicity	Fossil Fuels	Carcinogens	Public perception/acceptance	Trust in experts	Knowledge of CCS	Impact on other technologies	Perceived leakage	Impact on climate change	Perceived benefit	Perceived Cost	Perceived Health impact	Capital cost/ total cost	Cost of Electricity (COE	OPEX	EOR storage/ carbon price	Transportation cost	CO$_2$ avoided	Fuel price	storage cost	Capture cost	CO$_2$ leakage			Economic assessments	Life Cycle Analysis	Risk Assessment	Surveys of public perception	Scenario analysis	Energy integration/ comparison
1	🟩																							🟥			🟥			3	2	🟨					
2																						🟥		🟥						3	1	🟨					
3	🟩																			🟥	🟥	🟥	🟥	🟥		🟥	🟥			8	2					🟨	🟨
4	🟩	🟩	🟩	🟩	🟩		🟩													🟥	🟥	🟥				🟥			🟫	10	2	🟨	🟨	🟨		🟨	🟨
5	🟩	🟩	🟩	🟩		🟩														🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥		13	2	🟨					
6	🟩		🟩																		🟥		🟥		🟥	🟥				7	2	🟨				🟨	
7	🟩																						🟥						🟫	2	2	🟨				🟨	
8	🟩																			🟥	🟥	🟥	🟥		🟥					6	2	🟨					
9	🟩	🟩	🟩																	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥		12	2	🟨	🟨	🟨		🟨	
10																				🟥	🟥	🟥		🟥	🟥		🟥			7	1	🟨					
11																				🟥	🟥	🟥			🟥	🟥		🟥		7	1	🟨					
12	🟩				🟩																								🟫	2	2			🟨			🟨
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14											🟦	🟦	🟦				🟦													4	1				🟨		
15											🟦		🟦		🟦	🟦													🟫	4	2				🟨		
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Journal articles reviewed. 1 Dahowski et al. 2009. 2 McCoy and Rubin 2008. 3 Azar et al. 2006. 4 Viebahn et al. 2007. 5 Rubin et al. 2007. 6 Giovanni and Richards 2010. 7 van der Zwaan and Gerlagh 2009. 8 Rhodes and Keith 2005. 9 Hardisty et al. 2011. 10 Rubin et al. 2012. 11 Finkenrath 2012. 12 Ha-Duong and Loisel 2011. 13 Lampreia et al. 2011. 14 Terwel et al. 2009a. 15 Itaoka et al. 2009. 16 Fleishman et al. 2010. 17 Oltra et al. 2010. 18 Ashworth et al. 2009. 19 Anderson et al. 2009. 20 Huijts et al. 2007. 21 van Alphen et al. 2007. 22 Shackley et al. 2009. 23 Terwel et al. 2009b. 24 Terwel et al. 2012. 25 Nagashima et al. 2011. 26 Modahl et al. 2011. 27 Marx et al. 2011. 28 Khoo and Tan 2006a. 29 Khoo and Tan 2006b. 30 Koornneef et al. 2008. 31 Korre et al. 2010. 32 Nie et al. 2011. 33 Odeh and Cockerill 2008. 34 Gusca and Blumberga 2011. 35 Pehnt and Henkel 2009. 36 Singh et al. 2011a. 37 Singh et al. 2011b. 38 Singh et al. 2011c. 39. Sathre et al. 2012. 40. Zapp et al. 2012. 41. Schreiber et al. 2012.

The large variety of criteria used in the CCS studies reviewed makes it difficult to discern which criteria are most important for CCS analyses overall. The number of times each criterion was used in the 41 reviewed articles is calculated on the bottom row of Table 8. Global warming potential (GWP) was the most commonly assessed criterion (26 of the 41 studies) which makes sense as the purpose of CCS is to reduce GHG emissions. All the other criteria were far less commonly included across the studies with none of the other criteria used more than 20 times and most from six to nine times. The six most commonly used criteria, including GWP were all environmentally-focused. Social and economic criteria were quite equally represented (7.4 and 7.9 times per criterion, on average, respectively), but less than environmentally-focused criteria (11.7). Many studies did not: explicitly specify the functional unit of the assessment, indicate the life-span of the CCS project, outline the units for the indicators, nor state what the project boundaries were, which sometimes made comparisons between studies difficult. The functional unit is especially important as it declares results on a per unit basis (such as ‘per kWh’ or ‘per tonne of CO_2’), which clarifies the output and facilitates comparisons between studies.

4.4.1 Assessment of Interdisciplinarity

Across the 41 studies examined, the number of criteria included per study ranged from two to 13 with the majority including between four and eight criteria, and the median was seven (see the column in Table 8 entitled '# of criteria'). Eighteen studies were multi-disciplinary in nature, including criteria from two or more of the environmental, social and economic categories (see Figure 25). One study, (Lampreia et al. 2011) included criteria from all three areas, although it did not include CO_2 leakage. Two articles each covered two categories as well as CO_2 leakage. The majority of articles focused on criteria within a specific area with only one or two criteria outside its main area of focus. The most common examples were economic analyses that also include GWP, and environmentally-focused analyses that also include an overall economic criterion such as capital cost or cost of electricity. These results show that comprehensive multi-disciplinary studies on CCS are rare. This is hindering the understanding of the implications of CCS, which, as a complex technology, requires input from all fields of research to effectively develop.

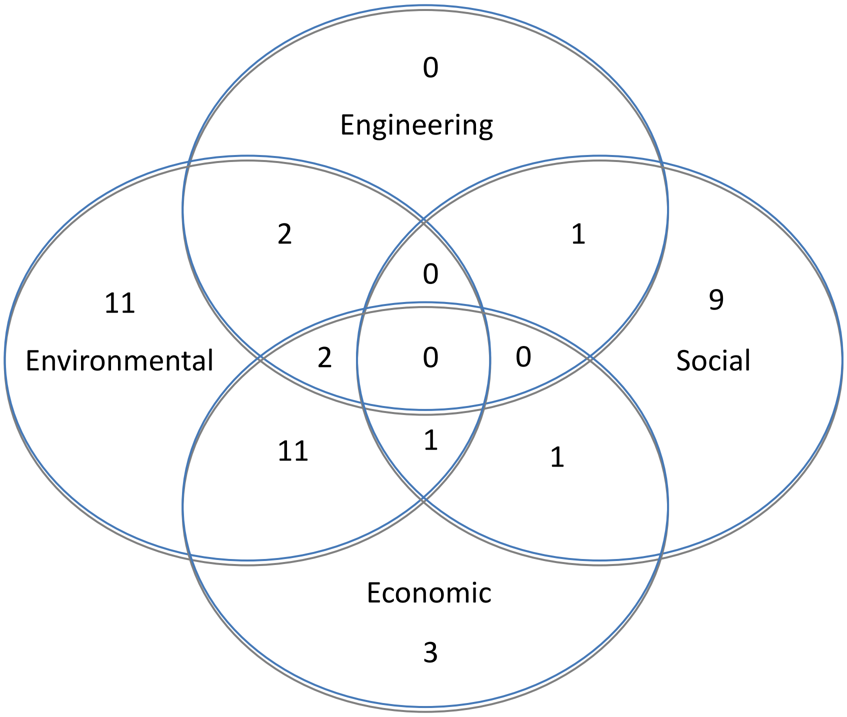

Figure 25 Number of reviewed articles parsed by the combination of disciplines assessed

Articles were further categorized based upon the predominant assessment method used. The assessment types were categorized as economic assessments (which included CBA as the most common assessment method), LCAs, surveys of public perception, scenario analysis and energy integration. LCAs were used almost twice as often as the next most used methods, appearing in 19 of the 41 articles, followed by surveys of public perception and economic assessments, which were used in eleven articles each. The articles almost always used only one method of analysis (see the column in Table 8 entitled '# of categories') with 33 of the studies using one, and only three articles using three or more methods. The studies that involved multiple assessment methods included more criteria than average. Using multiple assessment methods also meant that criteria were included from at least two areas (environmental and economic, or social and economic).

4.4.2 Economic Assessments

Amongst the 11 studies that had a predominantly economic focus, capital cost and cost of electricity were the most commonly used criteria. When environmentally oriented and socially-focused studies involved economic criteria, these were most often also capital cost and cost of electricity. This made these criteria the most common economic criteria overall, appearing in 13 and 12 of the 41 studies respectively. The remaining economic criteria appeared in between five and nine economically-focused studies each.

4.4.3 Environmental Assessments

All eighteen environmentally-focused studies and one economically-focused study used an LCA approach. Three of these studies were cross-disciplinary in nature, including risk assessments, scenario analyses and energy integration, as well as reviewing economic criteria. Almost every LCA article included global warming potential (GWP) or criteria such as CO_2 emissions or CO_2 intensity, which were considered to be comparable measures for this comparative analysis. Each of these criteria was aimed at describing how CCS impacts climate change through CO_2 emission reductions. Many studies looked at individual pollutants such as SO_2 or NO_x emissions. Others used more general measures of environmental impact such as eutrophication, acidification and land-use, each of which comprises several individual factors.

Based on the results of a previously undertaken and broader research PhD thesis study, LCA studies have been shown to be by far the most common assessment method for CCS in the literature. The environmentally-focused articles included in that broader study compared many variations of CCS, and also compared CCS to other climate change mitigation strategies, such as solar power or fuel switching (e.g. Viebahn et al. 2007), still the majority used an LCA approach. The broader CCS decision analysis research study strengthens the results of this interdisciplinary assessment study by providing more context.

4.4.4 Social Assessments

Almost all the social studies looked at public perception of CCS in some form. The other eight social criteria (Table 8) were each included in approximately half of the social study articles. It was found that social science studies on CCS tend to focus on only one or two areas such as public perception or perceived cost of CCS (Markusson et al. 2012). Social studies were generally not combined with environmental and economic assessments, with only two articles considering both economic and social aspects of CCS and one article spanning all three categories. Conversely, environmental and economic assessments also did not usually include any social criteria. This may be partly due to the different approaches used in these fields; social assessments conduct primary research by surveying public perceptions of CCS, whereas economic and environmental studies tend to integrate measured and estimated data collected in other studies.

The questions posed in the social studies were often project- or region-specific, considered a single type of CCS technology, and sought to elicit public awareness of the technology. Extrapolating to other CCS projects may therefore be problematic, given the project and geographic-specificity. Broader studies such as the Eurobarometer report do, however, provide a more general picture of public acceptance of CCS and can help indicate levels of support in different regions (Eurobarometer 2011). IPAC-CO_2 (2011) also released a study on broad awareness and public perception of CCS for each of the Canadian provinces, providing comparable data to the Eurobarometer study.

4.4.5 Engineering Factors

Beyond the decisions on what capture technology and transportation methods to use, CO_2 leakage from geological storage is one of the most important aspects of CCS. Most studies across all categories did not focus on the engineering and technical factors although they often discussed them, acknowledging that they may have a large impact on environmental, economic and social indicators. Indeed, there are studies focused specifically on assessing CO_2 leakage from geological reservoirs and its impacts (e.g. van der Zwaan and Gerlagh 2009; van der Zwaan and Smekens 2009; Ha-duong et al. 2009 and Little and Jackson 2010). In the broader assessment studies, CO_2 leakage was generally not explicitly included in the analysis, either due to the lack of data, or because it was outside the scope of those studies. Other major technical factors assessed in the reviewed articles are: plant efficiency, reservoir storage capacity for CO_2, power plant type, fuel type and electrical generation capacity, among others, but these were not included in the analysis due to the low frequency of inclusion. The energy penalty from adding CCS to a traditional power plant was also infrequently included in environmental and economically-focused studies. When adding CCS to a power plant, the energy penalty is the increase in fuel input (coal or gas) required to produce the same net energy output that would occur without CCS.

4.5 DISCUSSION

There are several factors that have limited the interdisciplinary nature of CCS studies and hindered the comparison between CCS studies. These have limited the holistic assessments of CCS which are needed due to its complexity and wide ranging impacts. In particular, the research conducted for this article has highlighted four main improvements that will enable interdisciplinary and holistic assessments of CCS: standardization of units and assumptions; in lieu of this, greater transparency in assumptions and units used; broader studies across multiple disciplines; and development of more commercial scale CCS projects which will allow for more up-to-date assessments. The remainder of this article will discuss these factors and recommend improvements.

Some patterns became apparent that made it difficult to compare the results from diverse studies. These included: a lack of transparency of methods and criteria used, unstated CCS project life-spans and boundaries, incompatible assumptions made between similar studies, and lack of a clear functional unit. It was therefore unclear exactly what was included in many studies.

Another challenge when comparing articles in this field is the rapidly changing and site-specific nature of CCS, which renders it difficult to obtain accurate and current economic, environmental and social data. Fundamental shifts in climate change science, public perception and mitigation technologies means that older studies quickly become incompatible with newer ones and new areas of research emerge. The cost of electricity, for instance, depends largely on engineering factors, external impacts such fuel prices, the local fuel and power generation capacity and the socio-political situation in a region. Other factors such as the location of a proposed CCS project, and its size and technologies proposed (i.e. a 400MW integrated combined cycle power plant or a 250MW post-combustion pulverized coal power plant, are likely to engender significantly different impacts, costs, and social perceptions for the project). The rapid development of this field also means that such assumptions are thus important to consider when comparing projects and drawing broader conclusions because there are very few large-scale CCS projects (and even these are mostly research or pilot projects) from which to gather information (Zapp et al. 2012). Therefore, no generally accepted set of assumptions exists. As more projects move towards commercialization, a database of actual CCS costs and social and environmental impacts could be developed in an overarching study similar to the IPCC Special Report on CCS (2005), summarizing impacts, and recognizing the significant changes in the past seven years since the first IPCC report (Kheshgi et al. 2012). This may also lead to industry-wide assumptions being established.

The reviewed papers comprise a wide variety of assessments of CCS in many geographic locations and taking different approaches. While each assessment provides a good analysis of specific situations, the lack of consistency makes it difficult to compare and extrapolate the wider implications of CCS, such as expected general costs of integrating CCS into power plants (Gabbrielli and Singh 2005; Di Lorenzo et al. 2012). Not only do assumptions and criteria vary across studies using a given method (e.g. LCA), but also assessments tend to exclude the factors or criteria used in other methods, especially social criteria. Marx et al. (2011) provide an analysis of LCAs used for CCS, and categorize some of the criteria used in those studies. The International Energy Agency Greenhouse Gas Program (IEAGHG) provides a summary of LCA studies showing 14 commonly used indicators (see Table 9) (2010). Much of the IEAGHG analysis focuses on the differing assumptions made and the data that are used in the studies. They also note that, although many studies on CCS have been performed, there is still a lack of sufficient data using comparable assumptions and criteria. Another IEAGHG (2009) report outlines 18 recommended criteria for selecting and assessing CCS storage sites. Our review builds upon the findings of the IEAGHG (2010), Markusson et al (2012), Marx et al (2011) and Allinson et al (2006) studies by looking more broadly at environmental, economic and social studies on CCS together as well as providing an analysis across the different decision assessment categories.

Table 9 Commonly used environmental indicators for CCS focused LCAs (Adapted from IEAGHG 2010)

Global warming potential
Acidification potential
Eutrophication potential
Photochemical oxidation potential
Ozone depletion potential
Human toxicity potential
Marine and fresh water aquatic ecotoxicity potential
Terrestrial ecotoxicity potential
Cumulative energy demand
Abiotic depletion potential
Particulate matter equivalent
Land use
Water use
Waste

Social and environmental studies can be assessed without reference to fully functional commercial CCS projects; social criteria can be assessed using scenario predictions, and environmental criteria can be assessed using data from components of CCS projects used in isolation. Economic studies, however, were found to be more generally tailored to specific circumstances (Allinson et al. 2006). As additional fully-integrated CCS projects are realized, it is expected that economic analyses will become more prevalent and also more accurate. In addition, the public is likely to become more aware of CCS and have better-formed opinions, which would provide an impetus for administering periodic public opinion and knowledge surveys.

The fact that GWP is overwhelmingly the most common criterion included in studies is partly due to the objective of CCS, which is to reduce the CO_2 emissions of fossil-fuelled power plants. The uncertainty surrounding the environmental impacts of CCS, and concern over its effectiveness as a climate change mitigation option, also likely influence the disproportionately large number of environmentally-focused studies found in the articles reviewed. Perhaps fewer studies assess social criteria partly due to the difficulty in quantifying the social impacts and public perceptions of CCS, the rapidly changing field of CCS, limited research funding, and a lack of awareness of CCS in general. The most common criterion assessed within the socially-focused studies was the overarching question of public perception of CCS, which was included in eleven studies.

4.5.1 Gaps in the Criteria Used in the Assessments of CCS

We looked at the environmental, economic and social categories to highlight gaps and inconsistencies between studies. Environmentally oriented studies focused primarily on GWP and CO_2 emission criteria, since CCS is aimed at mitigating climate change. Of the 18 environmentally-focused articles, 14 assessed GWP, while two articles used CO_2 emissions as a gauge for GWP. Sixteen environmentally-focused articles considered acidification whereas 14 articles looked at eutrophication potential, 15 at photochemical ozone creation potential and eight at terrestrial ecotoxicity potential. Although this is not an exhaustive list of studies that assess the environmental aspects of CCS, it does outline the significant differences between the scope of the articles. The addition of non-climate-change related criteria reflects the uncertainty of this climate change mitigation option, exacerbated by the limited number of commercial scale CCS projects and concern about potential impacts from CCS on other aspects of the environment. For example, the energy penalty for adding CCS to a power plant can increase the impact of the power plant by increasing fuel use, physical waste and mercury emissions amongst other side effects. Even when data on by-products are available, the risk implications are unclear when there is no contextual information against which to gauge the relative importance of each criterion. For instance, the relative increase in carcinogenic substances produced when opening a CCS plant may be significant, however if the original levels were very low, then the new increase may be negligible.

A concerted effort to determine which key CCS impact factors or criteria should be studied in general could benefit CCS project analyses. Many criteria were only included in a handful of studies, making their relative importance difficult to discern. On the other hand, more CCS evaluations will facilitate the assessment and comparison of criteria that are infrequently assessed. As the risks and impacts of CCS become better understood, unimportant criteria will eventually be filtered out of CCS studies to place more emphasis on key CCS issues.

Examination of the economic assessments of CCS reveals a similar pattern to the environmentally-focused assessments. Within the eleven economic articles reviewed, there were nine different criteria, with each article including from two to nine criteria. Although there were fewer economic criteria used in total compared to LCA studies, the economic criteria were more varied in their assumptions and in the units that were used, complicating comparisons and conclusions. It is not clear why this may be the case although Allinson et al (2006) provide a summary of economic CCS studies with respect to assessment assumptions and incompatibilities between studies which showed that the variation in assumptions led to significantly different cost estimates. As the CCS research field matures, these assumptions should become more uniform so that multiple studies can be compared on a consistent basis. Alternatively, factors for converting criteria units into common formats could be developed.

The social assessments analysed in this study were more difficult to compare as they comprised many questions that were very specific to local conditions, which can change dramatically across sites and over time. Most people are unaware of CCS and even those that are often do not have a strong understanding of the process (Eurobarometer 2011). Since public opposition has been a major contributor to CCS project cancellations (Anderson et al. 2012), a detailed assessment of local economic and social conditions is important and should be coupled with public engagement (Carbon Capture Journal 2010; Reuters 2011). Several articles noted low levels of awareness and limited knowledge of CCS, although the awareness and knowledge levels varied geographically (e.g. Huijts et al. 2007; Ashworth et al. 2009; Oltra et al. 2010; Fleishman et al. 2010; Itaoka et al. 2009). Providing more contextual information for the studies and gauging public opinion across more regions will allow for better assessments of the social factors that affect project viability. As only a few regions have been surveyed, there are many opportunities for further assessment of CCS perceptions, especially as CCS becomes more common and correspondingly more prevalent in the media.

4.5.2 Recommendations

The types of CCS impacts, their severity, and uncertainty, are still largely unknown and require further study. For high-level, comprehensive decisions, such as those involving CCS projects, environmental, social, and economic factors should be considered holistically, based on standardized or transparent assumptions. More high-level research needs to be conducted using this interdisciplinary approach. This will enable individual CCS projects to be compared with each other as well as CCS in general relative to other climate change mitigation options.

Such a broad-based approach should complement rather than subsume the detailed research into individual aspects of CCS. The evolving nature and uncertainty of CCS will continue to create new challenges and issues which should continue to be studied from multiple perspectives. The recommendations from this study are not meant to detract from research into criteria beyond those most commonly included. On the contrary, detailed, single-discipline studies are essential as they are the building blocks upon which broad interdisciplinary studies are built. However, if more single-discipline studies use benchmarked input data, standard assumptions, and common criteria in their assessments, it would allow for easier comparisons between studies. Foresight should be used when designing studies to both address the aims of the study, as well as enabling the findings to be integrated into the broader literature.

Key aspects that could be addressed in order to allow projects to be evaluated on a comparable basis are standardization and transparency, specifically regarding the length of CCS projects and boundary definitions, and use of consistent functional units. Critical event scenarios, where events outside the normal operation of a CCS project occur, such as CO_2 leakage or strong public opposition, can also to be included in future research. Each of these issues will be discussed in turn below.

Although some studies explicitly discuss the limits and boundaries of their assessments, especially within LCAs, many do not, leaving the reader uncertain as to which assumptions apply. A consistent evaluation method, which is explicit about which impacts are included and the length of project, is essential when comparing studies. Due to the long-term nature of CO_2 storage and liabilities associated with it, there is uncertainty surrounding the length of time after decommissioning that impacts should continue to be studied, and therefore how long a study should last. Due to these uncertainties and the need for long-term storage of CO_2, CCS projects could be considered to last between several decades to many hundreds of years. Over such long timeframes, small differences can have significant effects on the results. The *Canada Carbon Capture and Storage Statutes Amendment Act 2010 (Alberta)* provides some guidance on the reservoir conditions required before liability passes from the CCS operator to the government, although no firm length of time is given (Government of Alberta 2010).

The lack of a consistent functional unit or benchmarked input data hinders the ability to draw broader conclusions between LCA studies (IEAGHG 2010). To ameliorate this situation, a thorough investigation should be undertaken into the assumptions made in various studies, then applying a conversion of the results into a common functional unit based on kWh produced or tonnes of CO_2 stored. Although some studies do make many of their assumptions known, the functional units or units of the indicators are often not consistent with other studies. For example, Khoo and Tan (2006a) express eutrophication in terms of grams of NO_3 equivalent per kWh of electricity generated, whereas Koornneef et al. (2008) and others express eutrophication as grams of P_4^{3-} equivalent per kWh. For economic studies, costs are expressed usually in USD or Euros, however the reference dates are not usually stated, thus inflation effects and currency conversions cannot be accurately applied. This reflects a difficulty inherent to any new technology: a lack of standardized reporting methods and units and diversity of currencies used (Di Lorenzo et al. 2012). As mentioned previously, broader and more wide-ranging studies, such as the IPCC special report on CCS may help to set standards. Until CCS becomes commonplace, transparency is important.

4.5.2.1 Critical Event Analysis

Critical event analysis for CCS is another area that could benefit from more research. Critical event analysis refers to the assessment of the impact of significant negative events, such as the possibility of a CO_2 leak from the geological storage area, strong public opposition to the project, or significant pertinent regulation changes, amongst others. A CO_2 leak could have significant negative impacts on the majority of criteria assessed, ranging from health effects and GWP, to public perception and the economic costs of remediation. Only five studies explicitly included CO_2 leakage in their analysis. The limited number of studies including CO_2 leakage may be partially due to uncertainty over the probability and consequences of a CO_2 leak, or researcher and funding biases. When the potential for a CO_2 leak is not mentioned in a study, it can be assumed that it has not been implicitly included in the analysis. Such modelling assumptions are not inherently problematic, however, they should be clearly stated in future studies to aid in comparisons.

4.5.2.2 Sensitivity Analysis and MCDA Approach

Sensitivity analysis in general is lacking within CCS decision analyses. Placing an emphasis on reducing uncertainty by understanding both the possible range in values of parameters as well as their probability distributions, will help DMs better assess options (Markusson et al. 2012). A multi-criteria decision analysis (MCDA) approach is being adopted more commonly for energy decision analysis (Wang et al. 2009). MCDA methods can incorporate quantitative and qualitative data from environmental, social, and economic fields. They can also include sensitivity analyses to reflect the uncertainty in CCS estimates. A MCDA approach may be suitable for analysing high-level CCS decisions as it can include the insights gained from using multiple methods such as LCAs, economic assessments and opinion surveys.

4.5.3 Proposed Criteria

Markusson et al (2012) provide a starting point for assessments of CCS suggesting the following socio-technical areas of uncertainty for further research: variety of pathways; safe storage; scaling up and speed of development and deployment; integration of CCS systems; economic and financial viability; policy, political and regulatory uncertainty; and public acceptance. The proposed list of criteria in Table 10 created for this study builds upon Markusson's list in order to assess CCS holistically using a MCDA approach. For high-level comprehensive studies of CCS decisions, criteria should be included from each of the environmental, social and economic categories and also include risk assessments of critical events, especially CO_2 leakage. They could also include legal and regulatory criteria in specific circumstances. This table is constructed from the most frequently used criteria amongst the sample articles reviewed. In the absence of a better measure of the relative importance of criteria, the attention that has been paid by researchers to each one can serve as a viable surrogate measure. The list is subjective in that some criteria (e.g. trust in experts) were frequently used, but the authors thought that this would not be a useful universal indicator and thus only used when warranted. Conversely, CO_2 leak was not included in many studies, but should be retained due to its potentially large impacts on CCS.

Table 10 Proposed CCS assessment criteria

Environmental	**Social**	**Economic**	**CO_2 leakage**
GWP	Public perception/ acceptance	Capital cost	CO_2 leak
Air quality[9]	Knowledge/ awareness of CCS	Capture cost	
Eutrophication	Perceived benefit	Transportation cost	
Acidification	Perceived impact on other technologies	Storage cost	
Toxicity	Perceived impact on health	Operating cost	
	Perceived impact on climate change	Cost of electricity	

Also the proposed assessment criteria would provide a sufficient evaluation of CCS projects to allow decisions to be made without the DM becoming overwhelmed with too many criteria that do not have a significant impact on the overall objectives. The list should be considered as a minimum number of key criteria required for large-scale, high-level CCS decision analyses. With a limited number of LCA studies on CCS, there is still some uncertainty over which criteria are necessary (IEAGHG 2010) and the proposed list is expected to change as the field matures. This winnowing down of CCS options should occur alongside developments in the science of CCS with respect to capture technologies, transportation methods and storage mechanisms. The selection of technological, methodological and storage 'winners' will focus the CCS field and reduce the uncertainties in their impacts (Markusson et al. 2012). As circumstances warrant, there may be benefits from incorporating more or fewer CCS criteria in any given study. Broader CCS studies include many of the most common criteria. One of the criteria that should be included more often is the risk of, and impact from, a CO_2 leak, as it can have significant effects on other criteria. A consistent and systematic method is needed to incorporate CO_2 leakage into analyses (IEAGHG 2010).

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[9] This criterion could include indicators such as PM 2.5 and PM 10. There is a need for research into both air quality and toxicity to determine which indicators should be included.

Putting assessment standards in place either through the Canadian Standards Association (CSA), which is developing the first set of standards for geological storage of CO_2 in collaboration with IPAC-CO_2, or the European Committee for Standardization (CEN), or the International Association for Standardization (ISO), will provide the necessary consistency and guidelines for future assessments (CSA 2010; IEAGHG 2010). Such groups can provide industry-wide standards and guidelines for assessing CCS.

4.6 CONCLUSION

There are a wide variety of methods currently used to assess CCS. This reflects the evolving nature of CCS research in this emerging field. Currently, most studies are conducted within specific disciplines, predominantly environmental, economic or social. All three categories of study could benefit from using a more consistent set of units and clearer assumptions, in particular the environmental and social evaluations. Consequently, high-level, interdisciplinary studies would be better able to compare the detailed environmental, social and economic studies in their broad assessments. As more studies are conducted, methods for assessment should converge towards systematic approaches with more universal and transparent assumptions. This could be achieved through an adaptation of the current ISO 14000 series of environmental management standards or by a CCS-specific organization. This should reduce the uncertainty and variability in the results between studies and provide more general guidance for CCS decisions. As CCS is a rapidly changing field, more studies of all kinds, especially those related to pilot and demonstration plants, are greatly needed to better understand how CCS can contribute to mitigating climate change by reducing CO_2 emissions. Interdisciplinary studies fill the gaps of single-discipline studies by providing a broader and more comprehensive assessment of the CCS field.

4.7 ACKNOWLEDGMENTS

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CHAPTER 5

A MULTI-CRITERIA DECISION ANALYSIS MODEL AND RISK ASSESSMENT FRAMEWORK FOR CARBON CAPTURE AND STORAGE

This chapter outlines in a step-wise approach the risk assessment model for CCS using a multi-criteria decision analysis approach. The chapter uses a simple CCS example to demonstrate the elements of the model and provide a realistic decision analysis scenario as a potential use of the model. The chapter was submitted to the Journal of Risk Assessment. Dr. Ronald Pelot is a co-author on this article.

5.1 ABSTRACT

Decision making models using simple tools and including few alternatives have evolved into methods that assess decisions more comprehensively. Decision analysis now often utilizes more complex tools such as life cycle assessments, cost benefit analyses and high-level methods such as multi-criteria decision analysis (MCDA). MCDAs applied to energy decisions compare a variety of qualitative and quantitative criteria, usually spanning environmental, social, engineering and economic fields. These methods can also include risk analysis to address uncertainties in criteria estimates. One technology now being assessed to help mitigate climate change is Carbon Capture and Storage (CCS). CCS is a new process that captures CO_2 emissions from fossil-fuelled power plants and injects it into geological reservoirs for storage. It presents a unique challenge to decision makers (DMs) due to its technical complexity, range of environmental, social, and economic impacts, variety of stakeholders and long time-spans. The authors have developed a risk assessment model using a MCDA approach for CCS decisions such as selecting between CO_2 storage locations and choosing among different mitigation actions for reducing risks. The model includes uncertainty measures for several factors, utility curve representations of all variables, Monte Carlo simulation and sensitivity analysis. This article uses a CCS scenario example to demonstrate the development and application of the model based on data derived from published articles and publicly available sources. The model allows high-level DMs to better understand project risks and the trade-offs inherent in modern, complex energy decisions.

5.2 INTRODUCTION

Climate change is one of the largest threats facing humankind (Rackley, 2010). Carbon Capture and Storage (CCS) is a new methodology aimed at mitigating climate change by capturing CO_2, predominantly from fossil-fuelled fired power plants, and permanently storing the greenhouse gas in deep geological reservoirs (Natural Resources Canada, 2006). With the goal of reducing the magnitude of climate change, the Intergovernmental Panel on Climate Change (IPCC) has identified CCS to be one of several options needed in the 'portfolio of mitigation actions for stabilization of atmospheric greenhouse gas concentrations' (IPCC, 2005). The individual components of CCS (CO_2 capture, transport, and storage) have been implemented separately in many commercial-scale projects. CCS as a whole, however, incorporates all three components and has not been integrated with a power plant on a commercial scale as of 2012 (MIT, nd; IPCC, 2005; CO2CRC, 2010).

CCS refers to a process and not a single technology, as there are many different technologies that can be used to sequester CO_2 (Meadowcroft and Langhelle, 2010). The captured and transported CO_2 is injected into geological formations, such as depleted oil and gas reservoirs or subsurface saline formations. The compressed CO_2 remains as a supercritical fluid until a geochemical reaction gradually causes it to form solid carbonates. It takes CCS hundreds to thousands of years to permanently store CO_2 and effectively reduce climate change. During this time, CO_2 can potentially migrate hundreds of kilometers underground, affecting large geographic areas. These large timescales and geographic ranges can potentially impact many different environments, people, and incur significant costs. CCS has risks and uncertainty inherent to many new technologies, as well as risks unique to this technology and its application. Deciding how best to implement CCS is complex and would benefit from taking environmental, social and economic impacts into consideration in order to be utilised as an effective strategy for climate mitigation. These implementation decisions can be aided by the use of multi-criteria decision analysis (MCDA) tools (Huang *et al.,* 1995; Løken, 2007).

Traditional decision analysis methods such as cost benefit analysis (CBA) which use only economic indicators are not adequate to assess complex energy plans (Tsoutsos *et al.,* 2009). Single-discipline decision analysis methods cannot properly assess complex energy projects because the projects often have multifaceted impacts. Life cycle analysis (LCA), which assesses impacts (usually environmental) from projects throughout all stages of a project's life, is another common method used to address energy decisions but it also has limitations. Often, when decisions require an analysis of more than one criterion, there are tradeoffs that need to be made to achieve an 'optimal' solution[10]. Even with 'optimal' solutions, when risks and uncertainty are added to the analysis, there is no guarantee that the resulting decision will result in an optimal outcome. This occurs in part because the data used in making decisions is based on estimates which have a degree of uncertainty. For example, one project may have a lower mean expected cost but a higher-level of uncertainty than another project. The preferred option could be choosing the alternative with a lower expected mean outcome (e.g. CO_2 capture cost) with small variation in score rather than the alternative with a high expected mean but greater uncertainty in order to avoid potentially significant negative outcomes. Decision support systems often attempt to achieve an optimal solution through maximizing the expected utility of a project

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[10] An optimal solution occurs when there is no other option that will lead to a better outcome (DeGroot, 1970).

(Samson, 1988). Incorporating utility functions, which reflect DMs preferences on criteria values, can also help enhance decision making by assessing multiple criteria on the same scale.

MCDA refers to a broad category of methods used to assess non-monetary decisions along with, or separate from, monetary decisions. All MCDA techniques share a basic framework which enables the scoring of decision alternatives based on a set of criteria with user-assigned weights representing the relative importance of each criterion to the DM (Dodgson *et al.,* 2001; Gough and Shackley, 2006). MCDA puts an emphasis on weighting of heterogeneous criteria and including alternatives for a DM to choose from based on a common utility scale (Cavallaro, 2009). These methods are increasingly being used in complex energy modeling, which incorporate environmental and social aspects into energy decisions traditionally relying solely on economic analyses (Wang *et al*., 2009).

Previous CCS studies have attempted to reduce the uncertainty and to understand the risks of CCS projects by assessing CO_2 storage sites from a health, safety and environmental perspective (Oldenberg, 2008), environmental (Koornneef *et al.,* 2008). Others have reviewed CCS as an integrated process from an environmental perspective (Pehnt and Henkel, 2009; Hollman and Huber, 2010; Bouvart *et al.,* 2011; Sathre *et al.,* 2012), a socio-technical perspective (Markusson *et al.,* 2012), an economic perspective (Dahowski *et al.,* 2009), and in comparison to alternative climate change mitigation actions such as renewable energy (Viebahn *et al.,* 2012). Gough and Shackley (2006) and others (von Stechow *et al.,* 2011; Llamas and Cienfuegos, 2012) have used multi-criteria assessments to address CCS decisions.

The risk model developed here builds upon these other methods that have assessed energy decisions by incorporating more tools, including risk analysis, and assessing the decision in a holistic manner.

The authors' research has culminated in the creation of a risk assessment model incorporating MCDA to address CCS decisions. This application of the model is aimed at high-level DMs from governments or large, integrated energy companies. The risk model includes sufficient elements and criteria to accommodate comprehensive decision-making but it is not overly complicated so as to be cumbersome to a DM. It uses elements of LCA, CBA, MCDA, decision trees and additive model theory, and includes uncertainty measures, utility representations, Monte Carlo simulation and sensitivity analysis to help compare alternatives. The model is demonstrated herein using a realistic CCS scenario in which two mutually exclusive alternatives are being compared and was developed with data taken from journal articles and other publicly available sources to provide reasonable estimates of criteria values. The focus on high-level decision making allows users to better understand the tradeoffs between choices, as well as the risks associated with the different criteria.

5.3 MODELING PROCEDURE

The model procedure has four stages: decision model development, decision analysis, risk analysis, and project selection. These are made up of 13 steps (see Figure 26). Each step is described in detail in the remainder of this article using the example CCS decision scenario. Two realistic CCS projects (A and B) were developed to demonstrate the model.

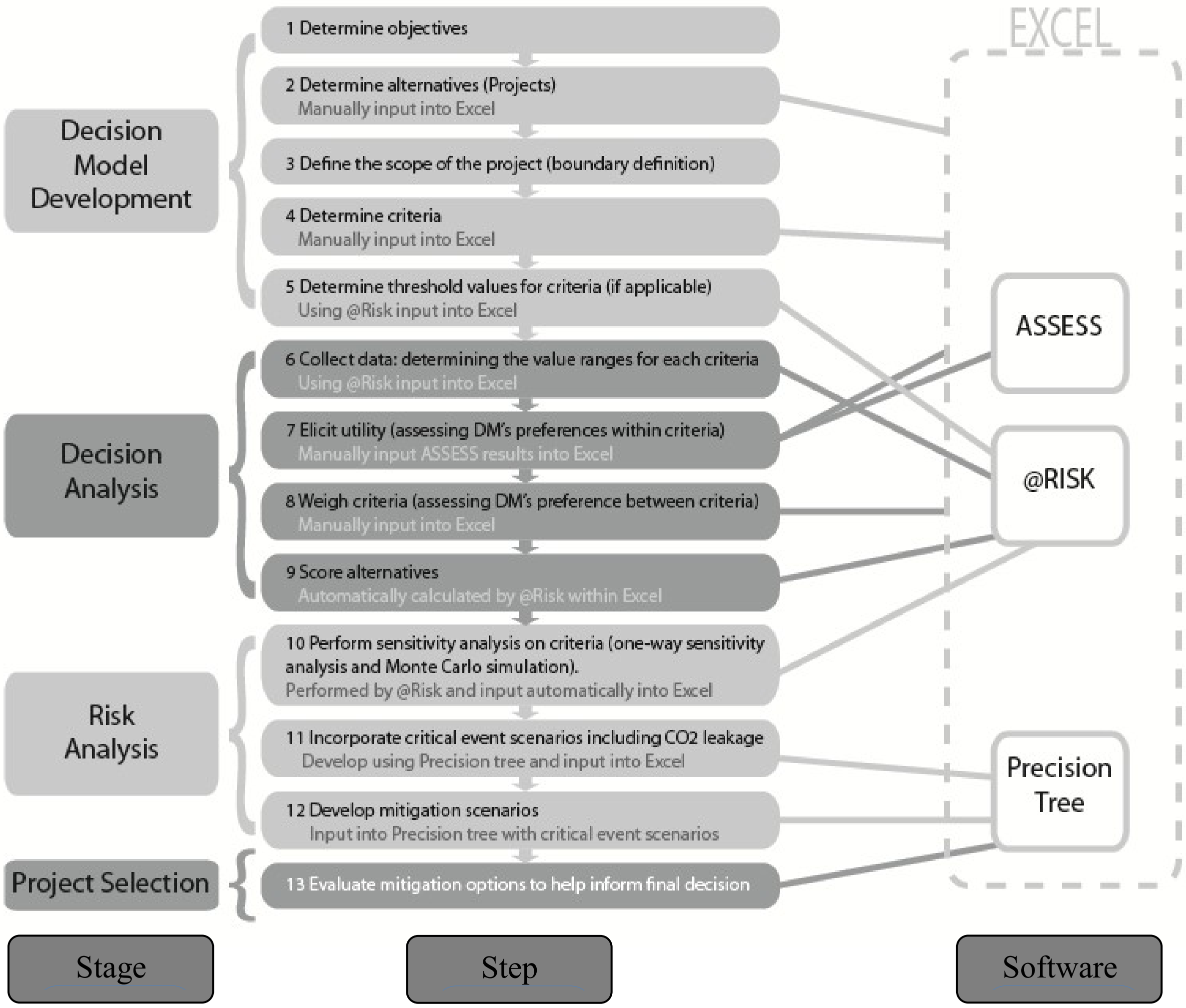


Figure 26 Procedure for MCDA CCS risk assessment model. The model must be performed in order but it can be an iterative process. The model uses four software programs (Excel, ASSESS, @Risk and Precision Tree). The software involved with each step is shown to the right of the graph. Excel is the primary user interface with @Risk and Precision Tree integrated directly, while ASSESS outputs have to be manually inputted into the system.

For the example in this study, we assume that the decision to pursue a new CCS project has already been made. The decision that the model is being used to evaluate involves selecting between two alternative CCS projects. Both of the CCS projects use post-combustion CO_2 capture technology on a coal power plant. The two projects are fully integrated CCS projects including CO_2 capture, transport and storage and each is to be considered holistically. The two CCS projects were developed based on data collected in a literature review of 41 CCS assessment studies, thus yielding estimates of possible values for each of the criteria (Choptiany *et al.,* in review). The 41 CCS studies provide sufficient data (between 6 and 22 data points per criterion) to produce probability density functions for each criterion. For instance, 22 articles provided data about the estimated global warming potential (GWP) (climate change impact factor) of power plants before and after CCS is added, ranging from a 36% reduction to a 91% reduction with a mean of 78%. Triangular probability distributions were created using the minimum, mean, and maximum values from the literature for each criterion. Expert opinion was used to remove rare outlier criteria data. The dataset also relied on experts to formulate two comparable but sufficiently different CCS projects in order to demonstrate the model. For the social criteria, Project A used public opinion survey data collected in Alberta, whereas Project B used data from Saskatchewan (IPAC-CO2, 2011). The specifications for the two devised projects are shown in Table 11.

Table 11 Description of Project parameters

Project parameter	**Project A**	**Project B**
Capture technology	Post combustion technology A	Post combustion technology B
Power plant output (MW)	500	500
CO_2 Transportation distance	50km	100km
Storage type	Depleted oil field A	Depleted oil field B
Geographic setting	Rural (Alberta)	Rural (Saskatchewan)
Project lifespan	40 years	40 years

A simplified schematic of the dataset for Project A is shown in Table 12. The table shows one realization of the data used to assess Project A. These include criteria units and values, weights, thresholds, scores, and utility functions. Each column represents a different step in the decision analysis procedure. Each row represents a different criterion contributing to the final decision. The criteria selected for this example are based upon a simplified list of criteria that are frequently used in CCS assessment studies (Choptiany *et al.,* 2012). The social and engineering thresholds were chosen to represent lower bounds while the environmental and economic criteria thresholds refer to upper bounds (see column 7 in Table 12). Since the model is based on probability density functions for each criterion, it is therefore probabilistic and the static data displayed in Table 12 represent just one possible outcome of the simulation (see Figures 29, 30 and 34 which represent probability distributions). The step in the decision analysis procedure that corresponds to each column is also displayed above the table.

Table 12 MCDA model database showing the order of the steps. Data is taken from Project A however the structure is the same for Project B.

Step:	**4**	**6**		**7**	**8**	**5**	**9**	
Area	**Criteria**	**Criteria Value**	**Units**	**Utility**	**Weights**	**Thresholds**	**Criteria score**	**Utility function**
Environmental	Global Warming potential (GWP)	0.159	% reduction in gCO$_2$-eqv/kWh	0.429	20	<0.5	8.58	(-)0.711+1.044*exp(-x-1.82)
	Eutrophication potential (EP)	-0.127	% reduction in gPO$_4^{3-}$eqv/kWh	0.473	5	<0	2.36	(-)2.307+2.879*exp(-x/-3.61)
	Human Toxicity potential (HTP)	0.018	% reduction in years of life lost	0.362	5	<0	1.81	(-)1.696+2.042*exp(-x/-2.16)
Social	Public perception of CCS	0.520	0-1	0.763	25	>0.02	19.07	2.082-2.322*exp(-x/0.92)
	Knowledge of CCS	0.314	0-1	0.409	4	>0.10	1.64	(-)1.599+1.299*exp(-x/-0.72)
	Perceived health impact	0.453	0-1	0.773	5	>0.05	3.86	1.433-2.606*exp(-x/0.33)
Economic	Capture cost	$85.54	$\$/\mathrm{tCO}_2$	0.342	15	<110	5.14	1.7736-.77*exp(-x/-10.79)
	Transport cost	$4.50	$\$/\mathrm{tCO}_2$	0.393	3	<7	1.18	2.426-1.195*exp(-x/-8.47)
	Storage cost	$8.15	$\$/\mathrm{tCO}_2$	0.243	3	<9	0.73	1.628-0.293*exp(-x/-5.25)
Engineering	Storage potential	29	Mt	0.816	22	>20,000	8.16	11.884-12.715*exp(-x/295.81)
	Enhanced oil recovery (EOR) revenue	$32.57	$\$/\mathrm{tCO}_2$	0.446	5	>5	2.23	1.709-4.644*exp(-x/25.01)
					100	**Total**	**52.53**	

5.3.1 Decision Model Development

The first phase in the decision analysis procedure is to develop the model framework. DMs must set out the fundamental objective for their assessment in Step 1, which in this example is to assess and select the best CCS project between two options (see Figure 27). The most important aspect of this step is to ensure that in projects with multiple DMs, agreement is explicitly reached between individual DMs' potentially disparate preferences for the fundamental objective. Once agreement is reached, DMs may outline the sub-objectives required to achieve the fundamental objective (Clemen, 1996). The sub-objectives of this example are to achieve the lowest costs, lowest environmental impacts, highest public support, largest CO_2 storage volume, and revenue from EOR operations. Reducing risks using mitigation actions is also a sub-objective of the model. Determining the objectives of the assessment guides what criteria and alternatives are included in the assessment.

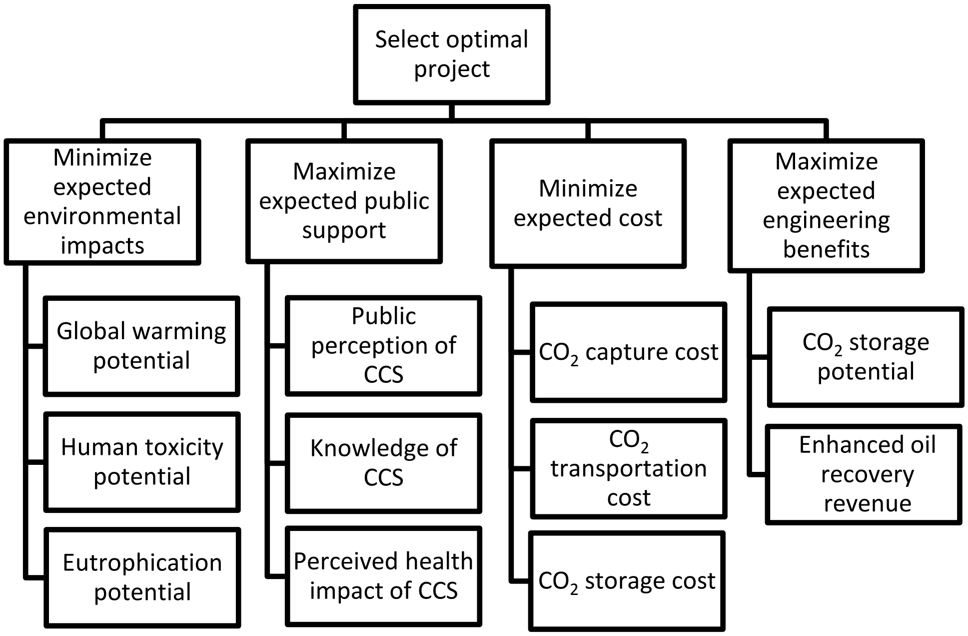
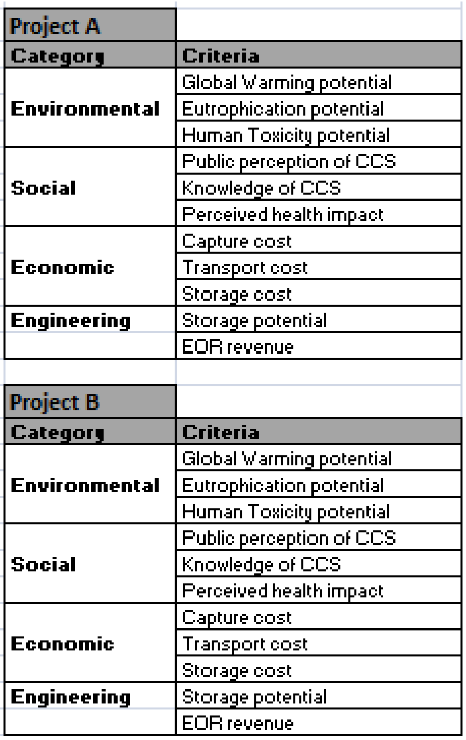


Figure 27 Main objectives and sub-objectives of the MCDA risk model example

Step 2, which involves determining alternatives, can be a multi-part step, depending on the depth of analysis. The first part involves setting out the available options. In this example, the two options or alternatives are the CCS projects. A DM may want to analyse the situation further and include several ancillary options in the analysis. Determining which alternatives to analyze may involve choices relating to specific elements such as changing technological components, when and how best to implement aspects of the project or how to prevent negative critical events from occurring. These options may reduce the uncertainty associated with some of the criteria by which the project is assessed, often engendering trade-offs such as reduced emissions at the expense of increased cost.

The geographical and temporal limits or boundaries for the project assessment are established in the third step. A consistent, suitable timeframe must be used to analyze the alternatives. For this example the timeframe is 40 years, the estimated lifespan of a typical CCS installation on a power plant. Moreover, all aspects of the projects will be assessed, from project planning to project decommissioning including the possibility of a CO_2 leak from the geological storage reservoir. As discussed below, only a select number of important project aspects will be considered for the analysis, since including every aspect of the project would be too complex and time consuming for DMs, with limited added value.

Next, the criteria need to be chosen in consultation with the key DM in Step 4. These are criteria that the DM deems important to the viability of a project such as capital cost or available CO_2 storage volume and should thus be considered when comparing alternative projects (see Figure 28 for Projects A and B). The criteria selected must provide sufficient detail to assess each project against the overall objectives or sub-objectives. This step in the MCDA CCS risk model development is where the framework for the two projects is laid out for comparison (see Figure 28). Subsequent steps build upon this framework to complete the assessment. A brief description of each criterion and its relevance to CCS is provided in Appendix 3A.



Project A	
Category	**Criteria**
Environmental	Global Warming potential
	Eutrophication potential
	Human Toxicity potential
Social	Public perception of CCS
	Knowledge of CCS
	Perceived health impact
Economic	Capture cost
	Transport cost
	Storage cost
Engineering	Storage potential
	EOR revenue

Project B	
Category	**Criteria**
Environmental	Global Warming potential
	Eutrophication potential
	Human Toxicity potential
Social	Public perception of CCS
	Knowledge of CCS
	Perceived health impact
Economic	Capture cost
	Transport cost
	Storage cost
Engineering	Storage potential
	EOR revenue

Figure 28 The two alternatives (projects) are entered into Excel to start the decision analysis framework. The criteria by which the projects will be compared are identical and categorized into Environmental, Social, Economic and Engineering for easy reference. Further elements of the model are added in subsequent stages.

Following the selection of criteria, the units of measurement need to be established and agreed upon to avoid confusion in later steps. For instance, the GWP criterion could be referring either to total GWP of the project, absolute reduction in GWP, or a percent reduction in GWP relative to a similar power plant project without CCS; thus, specificity is essential. It is important that the criteria are also consistent between alternatives. For example, although environmental and economic DMs may have different values with respect to various aspects of CCS, they can express those differences through their criteria weightings, but if these distinct groups do not assess the same criteria, then the assessments will not be comparable.

Although the overarching goal of CCS is to reduce CO_2 emissions, there are many other impacts that should be taken into consideration when assessing complex decisions. Each of these secondary impacts (criteria) must be defined before data is collected for each alternative. The risk that a project will score poorly on any given criteria can also be included in the model. For instance, there is uncertainty regarding what the actual capital cost of a project will be due to inherent variability in costs of materials and labour. As another example, a poor score on the public perception criterion could result in government cancelling funding or revoking a license for the project and thus would negatively impact the viability of the option.

Setting thresholds (Step 5) is optional, whereby a DM can choose to add limits to criteria values. These are specified upper or lower boundaries, beyond which the criterion is deemed to be unacceptable. Thresholds add another component to assessments, providing a DM with information about the probability of an alternative being unacceptable according to a given criterion. Examples could include setting thresholds for the maximum capital cost that a company can afford, minimum public support required for a social license to operate, or a minimum storage capacity for CO_2 to make the project worthwhile. Some thresholds such as health impacts or maximum cost can be strict, beyond which a project proposal may be abandoned. Other bounds, such as a minimum level of public support, may be used more as guidelines that could lead to extra measures being taken to improve the score of the project on that criterion. A DM may still choose an alternative even if it sometimes exceeds a threshold on a criterion, or if the probability of exceeding a threshold is very low. For example, the probability distribution of CO_2 storage capacity for Project A is shown in Figure 29. In this example, setting a minimum threshold of 23 Mt for any potential CCS implementation site signifies that there is a 15% chance of this location not having sufficient CO_2 storage capacity. Conversely, there is a 5% chance that this location can accommodate at least 28.5 Mt of CO_2 as shown by the right-hand tail in the Figure.

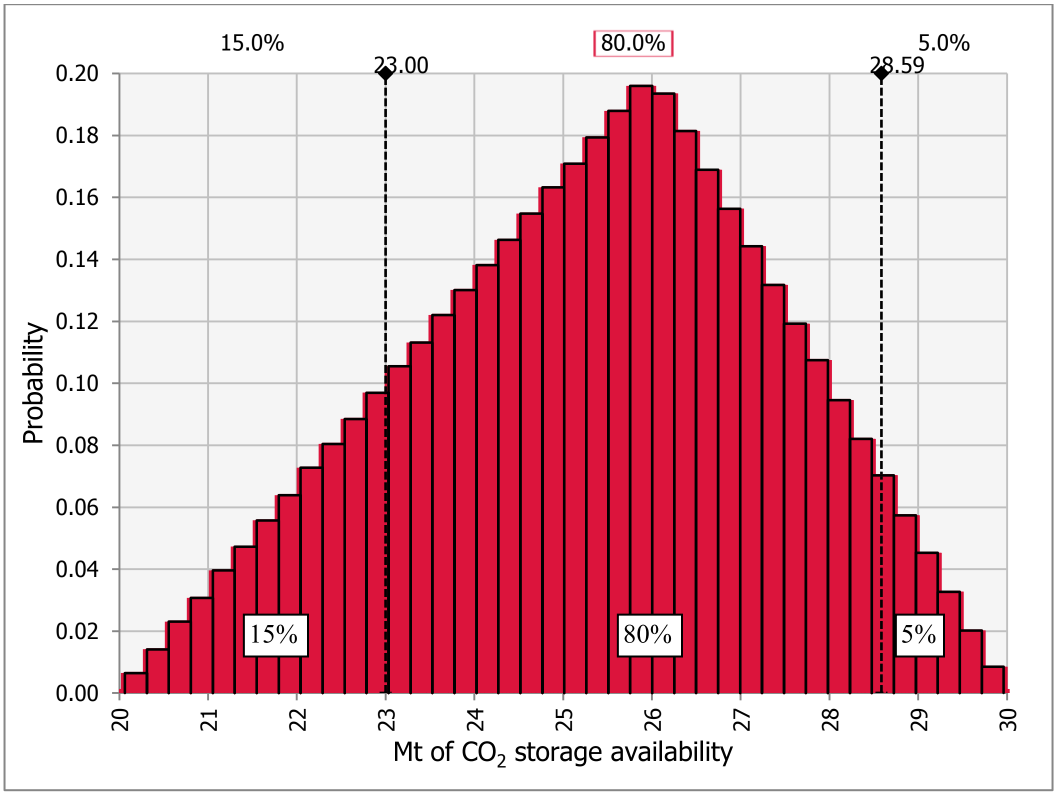


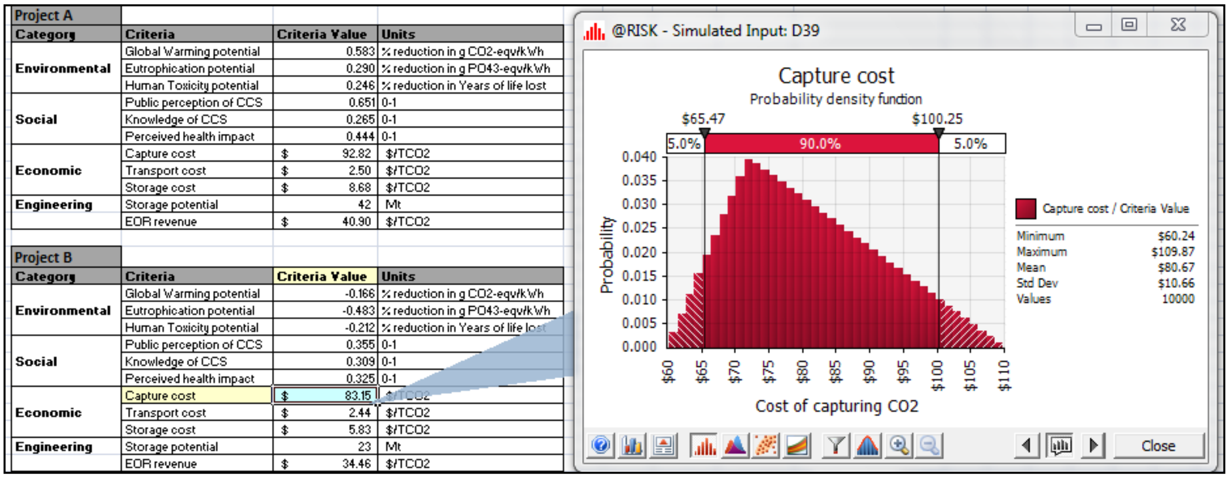
Figure 29 Probability distribution of CO_2 reservoir storage potential with a minimum requirement for 23 Mt of CO_2 storage

5.3.2 Decision Analysis

The decision analysis stage of the procedure involves collecting data and populating the model so that the model can be assessed (see Figure 26). The model framework is more fully developed in these steps (6 through 9) using Excel, ASSESS, @Risk, and Precision Tree software.

The data collection step (6) can be iterated throughout the assessment process as new information becomes available; however, criteria weighting and utility curves may need updating if this is done to reflect the new data's impact on DM's preferences. Front end engineering and design (FEED) studies, in-house calculations, manufacturing data, expert opinion, public opinion, LCAs and peer-reviewed papers can used to develop a database from which relevant CCS project values can be assigned to each criterion. Interpreting the data and including uncertainty parameters can be contentious aspects of the assessment as there is often some subjectivity in developing probability distributions due to different degrees of quality of input data. Projections into the future (in this example approximately 40 years) are needed to form estimates of how the technologies and other uncertain factors will evolve. Future technology projections are highly subjective as some applicable technologies are still quite new and there are also many external factors impacting the projects. This model demonstration assumes a single stage decision between Projects A and B based on the available data, however it should be noted that as new information becomes available or conditions change, aspects of the model can be rerun.

Best available data and expert opinion are needed to determine how to use uncertainty information most effectively when developing the criteria database. As data is input into the decision analysis framework, the model grows and the data changes from representing a single number to representing a distribution of possible numbers (see Figure 30). For example, a representative probability distribution on the range of CO_2 capture costs is illustrated in the right side of Figure 30. Triangular probability distributions were used for each criterion in this example as it is a good approximation when given limited data (Decision Sciences, 2000).



Project A

Category	Criteria	Criteria Value	Units
Environmental	Global Warming potential	0.583	% reduction in g CO2-eqv/kWh
	Eutrophication potential	0.290	% reduction in g PO43-eqv/kWh
	Human Toxicity potential	0.246	% reduction in Years of life lost
Social	Public perception of CCS	0.651	0-1
	Knowledge of CCS	0.265	0-1
	Perceived health impact	0.444	0-1
Economic	Capture cost	$ 92.82	$/TCO2
	Transport cost	$ 2.50	$/TCO2
	Storage cost	$ 8.68	$/TCO2
Engineering	Storage potential	42	Mt
	EOR revenue	$ 40.90	$/TCO2

Project B

Category	Criteria	Criteria Value	Units
Environmental	Global Warming potential	-0.166	% reduction in g CO2-eqv/kWh
	Eutrophication potential	-0.483	% reduction in g PO43-eqv/kWh
	Human Toxicity potential	-0.212	% reduction in Years of life lost
Social	Public perception of CCS	0.355	0-1
	Knowledge of CCS	0.309	0-1
	Perceived health impact	0.325	0-1
Economic	Capture cost	$ 83.15	$/TCO2
	Transport cost	$ 2.44	$/TCO2
	Storage cost	$ 5.83	$/TCO2
Engineering	Storage potential	23	Mt
	EOR revenue	$ 34.46	$/TCO2

Capture cost / Criteria Value	
Minimum	$60.24
Maximum	$109.87
Mean	$80.67
Std Dev	$10.66
Values	10000

Figure 30 The criteria values and units for each project are entered into Excel. Each criterion value shown as a static number in the Excel table on the left represents a single instanced sampled from a probability density function shown on the graph on the right side.

Once the information, including uncertainty estimates, has been collected and collated into a database, a utility curve of the DM's preferences must be developed for each criterion. This step (7) fulfills two major functions: to enable all criteria to be compared on the same scale of 0-1; and to assess the DM's preferences for criteria values along the spectrum of worst to best case. Utility is used as a measure of the usefulness of an item to a person or to represent their preferences for incremental increases or decreases in the value of an item. To compare heterogeneous alternatives (with heterogeneous units), it is essential to use the same scale for all criteria; in this case utility or 'utility units' (Clemen, 1996). In order to do this, utility curves and utility functions are often used. Once utility curves are generated for all criteria, each criterion can be expressed in terms of utility and compared with the other criteria using the same scale.

Decomposing large decisions into their component questions can often result in decisions that more accurately reflect preferences. Utility functions (an equation representing a utility curve) are therefore elicited using questions about specific circumstances to determine preferences on individual criteria. Utility elicitation involves measuring a DM's relative preferences between different values on a single criterion. There are several methods for eliciting preferences. One is asking a DM to rate how much better or worse two values of a criterion are, such as a CO_2 capture cost of \$80/tCO_2 relative to a cost of \$90 on a scale of 0-1. Another method involves presenting a series of reference gambles or lotteries based on two options in order to find the point at which both options are deemed equal and the DM is indifferent between the options (Holloway, 1979). The latter method is employed for this article. Once a series of questions are asked to determine indifference points, a curve can be generated and a mathematical function fitted to it. The general procedure is described in Table 13. This process would then be repeated for each criterion. This is an important step because utility/preferences are generally non-linear as people can be categorized as risk-takers or risk-averse (Eisenhauer, 2006). Since a criterion value for a particular option can vary when performing a sensitivity analysis or due to uncertainty in its estimates, the preferences must also change commensurately. Instead of asking the DM their preferences for all possible values, an equation is developed automatically to represent their changing preferences. Utility typically exhibits diminishing returns for most criteria as its values increases. In Figure 31 we can see that as the criterion CO_2 capture cost decreases, the rate of utility decline increases, indicating that each subsequent increase in cost is worse than the previous increase. The sample data for curve fitting is also shown, which derive from the responses to the lottery-based questions.

Table 13 Procedure for creating utility curves. (Adapted from Holloway, 1979)

1. Establish the range of possible values for the decision problem. The minimum and maximum values possible for the criterion should be used as the bounds of the decision. Utility is generally set between 0 and 1 with 0 representing no utility and 1 representing maximum utility.
2. A DM is told that they have a fixed percentage chance of winning a gamble. They can choose this gamble based on this percentage chance or alternatively accept a fixed value (safe bet). For example they could choose to pay \$23, or gamble with a 50% chance of paying \$0 or 50% of paying \$50. Each time the DM makes a choice, (based on new fixed values and outcome percentages) how their preferences vary for the criterion will become clearer until the two options are considered equal. The point where the DM believes both options are equal represents an indifference point. The expected outcome of the gamble is the utility equivalent to the criterion value chosen as the point of indifference. This process is repeated until a sufficient number of points are created to develop a trend line to represent the data points (usually a minimum of 5).
3. Record the indifference points (criterion values) on a graph with utility on the vertical axis and criterion value on the horizontal axis (see Figure 31).
4. Once enough choices are made (and indifference points created), a curve can be fit to these data points and an equation developed.

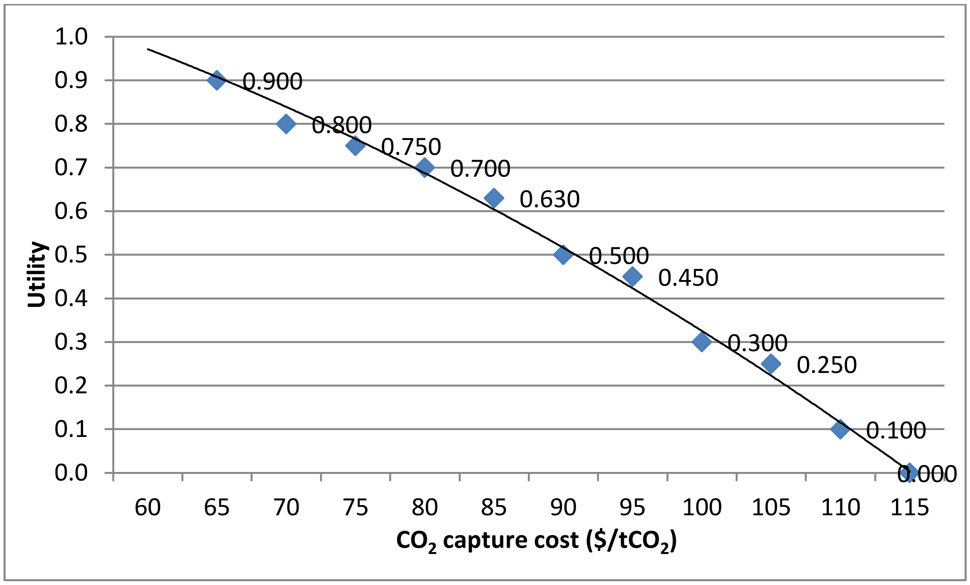


Figure 31 Utility curve as a function of CO_2 capture cost

The preferences used to generate the utility curve in Figure 32 were elicited with a software program (ASSESS), using probability lotteries (Delquie, 2008). The utility function representing the utility curve (created using ASSESS) is displayed in Equation 1. ASSESS fits a curve to this data and produces the function for the curve. Utility curves are also used in the Monte Carlo simulation described below in Step 10. The utility function can be used to estimate a DM's preference at any value within its upper and lower bounds.

$$\boldsymbol{u(x) = 1.7736 - 0.77^{(\frac{-x}{10.79})}} \qquad \text{Equation 1}$$

Thus u(x=115) = 0 and U(x=60) = 1.

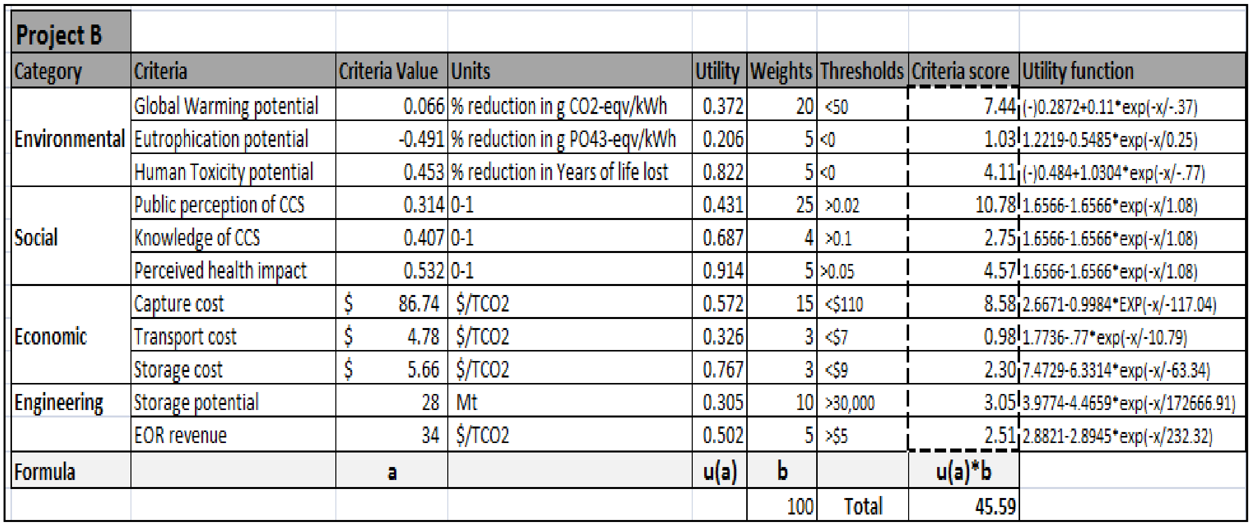
The range of values used in a utility assessment is important and should be based upon the expected best and worst values using the criteria database. Using bounds based on the minimum and maximum values of the criteria enable realistic differences between alternatives to be highlighted. However, utility curves need to be recreated if a subsequent option is added to the decision analysis that has criteria values outside the original assessment bounds. Following the proposed methodology outlined in Figure 26 sequentially and thoroughly at each step is thus very important in order to avoid repeating steps.

The methods and values used for developing utility curves are important due to the 'anchoring' phenomenon (Tversky and Kahneman, 1974). The reason for this is that the initial values that a probability lottery starts with to elicit utility will be taken by the layperson as normal. For instance, if a DM were asked to rate their preference between transport costs of \$40/tCO_2 versus \$45/tCO_2, they may believe that those costs are representative of typical transport costs rather than costs closer to \$5-10/tCO_2 (ZEP, 2011). Thus, starting values provided would influence a layperson DM, which will skew their answers if the values are not within a reasonable range of the real data (Holloway, 1979). This is less likely if DMs have pre-existing knowledge of what constitutes reasonable values. Providing contextual information to the DMs about the criterion being assessed can also help if they are not experts in that field. A knowledgeable DM with contextual information about each criterion will therefore provide more robust utility curves.

Criteria weighting (Step 8) serves to determine the DM's preferences between criteria. The relative importance of each criterion to a DM's overall decision dictates the weight assigned to each criterion in the model (see column 6 in Table 11 for the weights used in the example). The initial selection of criterion weighting requires contextual information (similar to utility elicitation) to be provided to the DM and this information should be determined with an understanding of the actual projects being studied to provide realistic reference values for the criteria. For example, when assigning weights to capture cost and storage cost, the relative weights would be different knowing that the transportation costs were \$4/tCO_2 rather than \$40/tCO_2, when comparing with a capture cost of \$80/tCO_2. A DM may weigh the \$80/tCO_2 as 20 times more important than \$4/tCO_2 rather than twice as important as \$40/tCO_2. Moreover, the criteria need to be assessed holistically and relative to each other instead of in isolation. The weights, however, are specific to the criteria and not to the projects, so the final set of weights are the same for each project. The criterion weights will stay consistent throughout the analysis as they are based on the criterion's possible values. These concepts will be explained in more detail below as further steps of the model are described.

This sample model is meant to be simple and transparent yet incorporate all the necessary elements for a comprehensive decision assessment. In this example, a DM would allocate 100 points across all criteria based on how the DM rates the importance of each criterion. The only requirement would be that each criterion must be weighted between 0 and 100 and that all 11 criterion weights sum to 100 points. Because each project's criteria can have a maximum utility score of 1 and they are multiplied by the weights which sum to 100, each project can have a maximum possible score of 100 (i.e. if the project scored perfectly on all criteria). The model is a comparative analysis, therefore a project's score has no inherent value; it must be compared to another project using their relative scores.

Scoring is a relatively simple step (9) involving multiplying the utility score of an alternative on one criterion by its assigned weight. Scores for each project's criterion are then summed to create an overall score for each project (see column 9 in Table 11 and Figure 32). Running the model numerous times using Monte Carlo analysis to sample each time from the uncertain variables. A mean expected score for each project can then be created. Further methods of assessing project viability are described in Step 10.



Project B								
Category	**Criteria**	**Criteria Value**	**Units**	**Utility**	**Weights**	**Thresholds**	**Criteria score**	**Utility function**
Environmental	Global Warming potential	0.066	% reduction in g CO2-eqv/kWh	0.372	20	<50	7.44	(-)0.2872+0.11*exp(-x/-.37)
	Eutrophication potential	-0.491	% reduction in g PO43-eqv/kWh	0.206	5	<0	1.03	1.2219-0.5485*exp(-x/0.25)
	Human Toxicity potential	0.453	% reduction in Years of life lost	0.822	5	<0	4.11	(-)0.484+1.0304*exp(-x/-.77)
Social	Public perception of CCS	0.314	0-1	0.431	25	>0.02	10.78	1.6566-1.6566*exp(-x/1.08)
	Knowledge of CCS	0.407	0-1	0.687	4	>0.1	2.75	1.6566-1.6566*exp(-x/1.08)
	Perceived health impact	0.532	0-1	0.914	5	>0.05	4.57	1.6566-1.6566*exp(-x/1.08)
Economic	Capture cost	$ 86.74	$/TCO2	0.572	15	<$110	8.58	2.6671-0.9984*EXP(-x/-117.04)
	Transport cost	$ 4.78	$/TCO2	0.326	3	<$7	0.98	1.7736-.77*exp(-x/-10.79)
	Storage cost	$ 5.66	$/TCO2	0.767	3	<$9	2.30	7.4729-6.3314*exp(-x/-63.34)
Engineering	Storage potential	28	Mt	0.305	10	>30,000	3.05	3.9774-4.4659*exp(-x/172666.91)
	EOR revenue	34	$/TCO2	0.502	5	>$5	2.51	2.8821-2.8945*exp(-x/232.32)
Formula		**a**		**u(a)**	**b**		**u(a)*b**	
					100	Total	45.59	

Figure 32 Completed database for Project B. The light gray shaded row entitled ‘Formula’ shows the relationship between the columns. Criteria value is the Project-specific data for each criterion. Utility (shown in the last column) is a function of the criteria value, established using the ASSESS software. Weights are a DM-assigned value based on the importance to the overall project selection. Criteria score is a function of utility multiplied by the weight and is outlined with dash lines. The total project score is the sum of all criteria scores.

5.3.3 Risk Analysis

Step 10 involves performing a sensitivity analysis on the data, treating the variables (criteria) independently. Sensitivity analysis is used to explore the inherent uncertainty surrounding such large-scale CCS projects, and has been used to similarly address energy problems (Abu-Zahra et al., 2007; Di Lorenzo *et al.,* 2012). One-way sensitivity analysis is a method whereby criteria can be explicitly varied by a set amount (usually by a percentage change around the expected mean, or specific to a criterion if its uncertainty distribution is known), to see the impact of changes to an individual criterion on the overall project score (Clemen, 1996). The range of the impact on a project’s score is thus a function of how important a criterion is to a DM as well as how much the data varies. For instance varying a criterion which has a large uncertainty, but a low DM weight may not have a substantial impact on a project’s score.

Using the data from a one-way sensitivity analysis, a Tornado diagram can be created to show the variation in expected value on the final project score as a function of a predetermined variation of each criterion value. The criteria that have the largest impact on the final score (i.e. the largest range) are shown on top, with less influential criteria below. This results in a diagram that resembles a tornado (Figure 33). This process can identify large uncertainties in the project scores and highlight areas where better information about criteria values could significantly improve the reliability of a project's score. Sensitivity analysis can also be used to determine how much a criterion value must change before the overall rankings of projects change. Finally, this type of analysis shows the DM how sensitive the results are to external factors.

In this example we varied each criterion by ±10% of its mean which resulted in public perception having the largest impact on the project's score (see Figure 33). The mean scores for the projects are only 6% different (see Table 14 and Figure 34). Since the potential impact of each criterion that is varied in the sensitivity analysis can increase or decrease the project score by more than 6%, changes in each criterion have the potential to influence the selection of projects. This shows us that the decision to select between the projects is very sensitive to variations in the criteria scores and would not be well described by only using the mean scores. Varying each criterion by ±10% of its mean was done to simplify the example by not taking into account the expected variation in criterion scores. Often the criteria are varied by a prescribed number of standard deviations in order to account for the difference in uncertainty between the criteria.

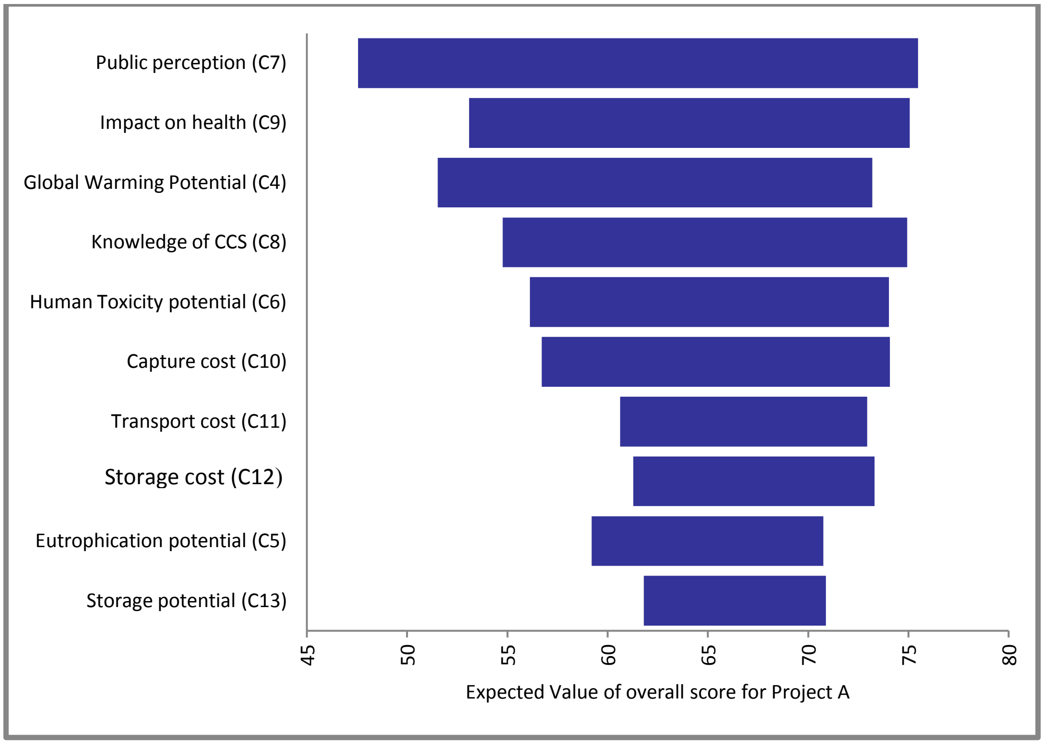
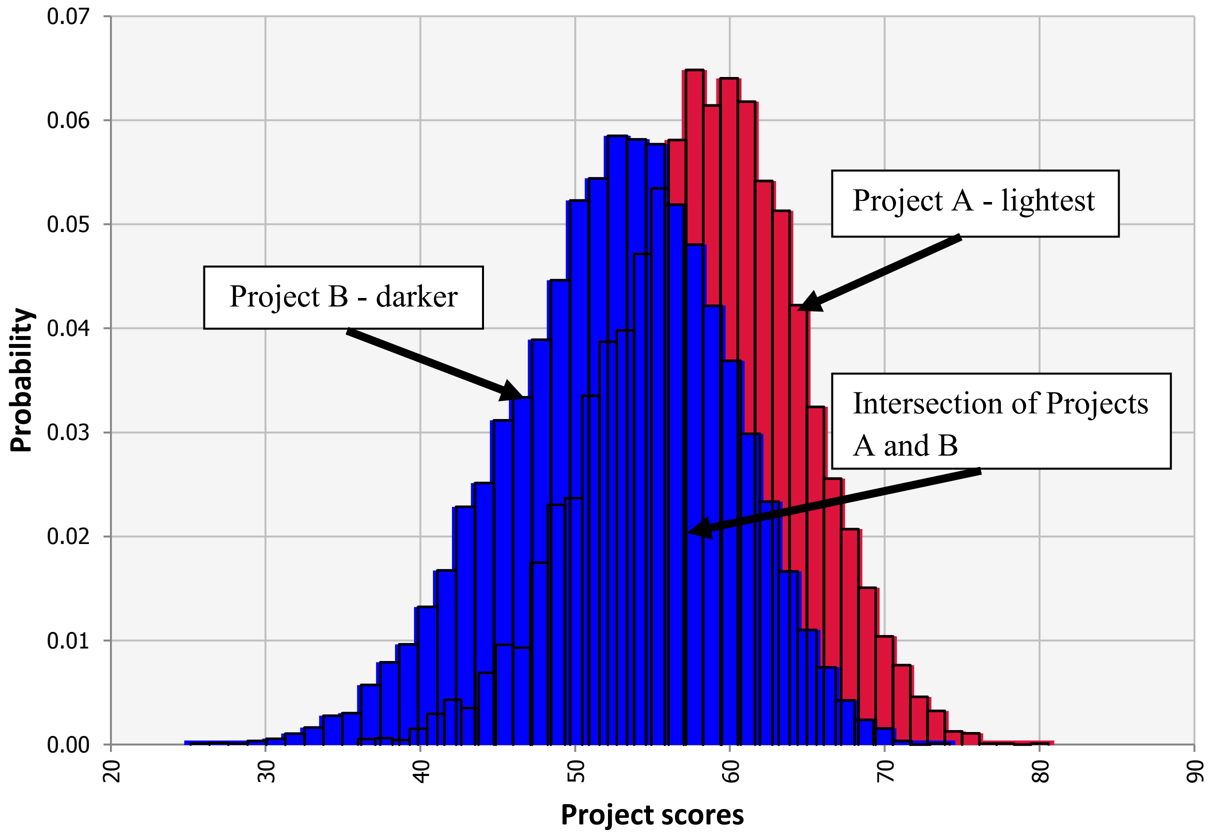


Figure 33 Tornado graph for CCS decision using a one-way sensitivity analysis where each criterion's mean value is varied by ±10%

Monte Carlo simulation can be used to explore the effect of the probability distribution of the criteria values on the overall viability of the alternatives. This method is commonly used to assess large-scale projects (Ho and Pike, 1998) and has been used to address CCS-specific problems (Rao and Rubin, 2002). This provides more information to the decision maker than simply the estimated mean and standard deviation for each alternative's score, which are often very uncertain (Di Lorenzo *et al.,* 2012). Monte Carlo simulation is a method that involves sampling repeatedly from probability distributions (Clemen, 1996). Since a probability distribution was developed for each criterion in this example, there is uncertainty about what their actual scores will be (Di Lorenzo *et al.,* 2012). Monte Carlo simulation samples multiple times from probability distributions to determine the possible outcomes using all combinations of input data already collected (Samson 1988). As we have already developed utility curve functions and probability distributions for the criteria, we can run Monte Carlo simulation automatically for thousands of iterations in combination with the uncertain criteria data and utility curves. Unlike one-way sensitivity analysis, Monte Carlo simulation varies all input data simultaneously to examine the overall variation in outcomes based on DM preference and uncertainty in criteria values (Di Lorenzo *et al.,* 2012).

The outcome of the Monte Carlo simulation shows that Project A would likely be chosen as the preferred project with its probability distribution of scores significantly higher than Project B's scores (Figure 34). Project A has a mean score of 58.17 which is only moderately higher than Project B at 52.62 (see table within Figure 34). The possible project scores overlap, therefore during the Monte Carlo simulation there is a 19.56% chance that Project B has a score that is higher than Project A. Determining the likelihood of a project achieving a higher expected score was done by summing the instances on the Monte Carlo simulation where the score of Project B was higher than Project A. For instance, when project scores are substantially different further analysis is usually not required, however when they are quite similar, Monte Carlo analysis can enable a DM to delve deeper into the projects and provide more information to DMs to better understand the conditions under which any project is superior in order to improve decision making. The large range in potential scores, between 23.89 and 78.49, illustrates the large uncertainty in project scores and that simply choosing a project solely using expected mean score does not adequately describe the two projects.

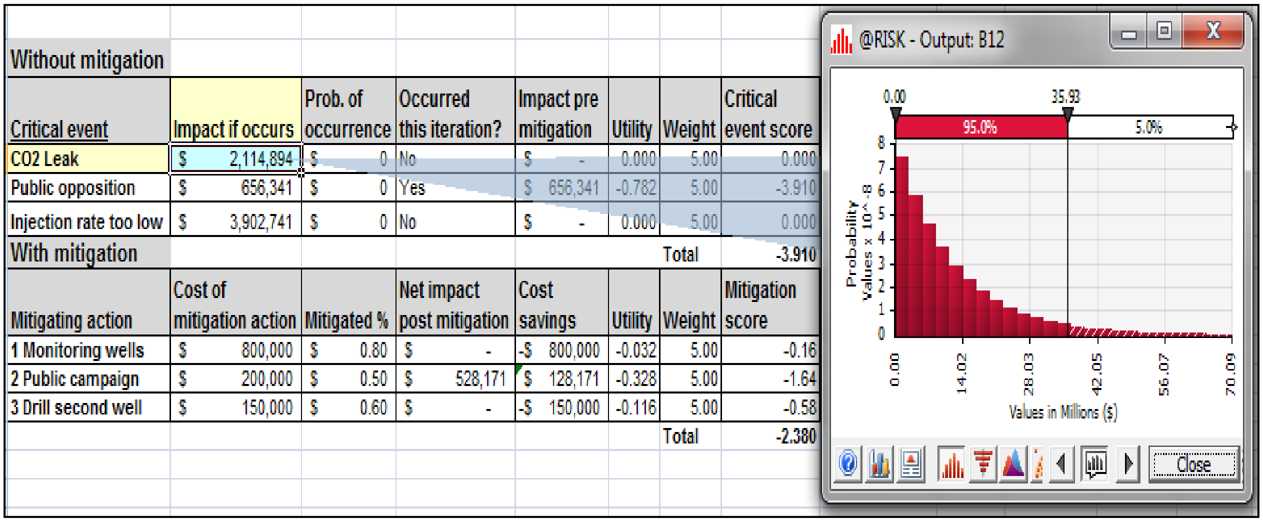


	Mean	% preferred choice	Minimum	Maximum
Project A	58.17	80.44	34.37	78.49
Project B	52.62	19.56	23.89	72.43

Figure 34 Probability density functions for the scores of Project A and Project B. Project A has the higher score for 80.44% of the 10,000 Monte Carlo simulations. The mean, minimum and maximum scores for the two projects is shown in the table at the bottom of the figure.

CCS has many risks that can be addressed in a risk assessment. For example, there are many uncertainties involved with the cost of CCS and what the exact impacts will be on public perception and environmental criteria. However, a greater risk surrounds the potential for a major event to derail a project, such as a CO_2 leak anywhere along the capture, transport, injection and, especially, storage pathway. Le Guenan *et al.,* (2011) for instance describe eleven storage risks for CCS, all dealing with CO_2 leakage. Although there are many different event scenarios that could lead to a CO_2 leak, they all represent varying degrees of risk to a CCS DM. Estimating the probabilities of these events, their magnitudes and effects on the various criteria values is very difficult due to limited data. It requires the input of expert opinion and available data from real-world pilot injection sites, such as those being conducted at the Weyburn-Midale project in Saskatchewan (PTRC, 2004). As with criteria value uncertainties, these critical events can be input into Monte Carlo simulations to evaluate many possible scenarios.

Step 11 involves incorporating critical events into the analysis and determining what mitigation actions could be introduced to lessen their impacts. The analysis so far only includes uncertainties surrounding the establishment and normal operations of a CCS project. Critical event analysis looks at possible events that could occur that would change the values of the criteria beyond normal conditions. In this example we consider three critical events: a CO_2 leak from a storage reservoir, strong public opposition to a CCS project, and a storage reservoir that does not allow for CO_2 to be injected at a high enough rate to be economically viable. Three mitigation options were also developed to reduce the severity and/or likelihood of these critical events. These include using more CO_2 monitoring wells, a public outreach campaign, and drilling extra injection wells, respectively. Estimates of the probability and severity for each critical event were established using the literature data collected for this demonstration (see Figure 35 for an example when public opposition does occur but the other two events do not). A utility scale is set for each type of critical event. In the case where no critical event occurs, the utility is 0, and for the worst case of that event, the utility is -1. The DM must establish a weight for the relative importance of each critical event, based on how important they believe it is to the viability of the project. The critical event weights do not need to be equal and should be set in relation to the other criteria being considered, but in this example they have all been set at 5.0. Therefore, the maximum possible score for each event is 0, whereas the most negative score (i.e. penalty) for each critical event in this example would be 5, which is subtracted from the project's score. The project score would be reduced proportionally less based on the severity of the critical event if it occurs.


Without mitigation

Critical event	Impact if occurs	Prob. of occurrence	Occurred this iteration?	Impact pre mitigation	Utility	Weight	Critical event score
CO2 Leak	$ 2,114,894	$ 0	No	$ -	0.000	5.00	0.000
Public opposition	$ 656,341	$ 0	Yes	$ 656,341	-0.782	5.00	-3.910
Injection rate too low	$ 3,902,741	$ 0	No	$ -	0.000	5.00	0.000
						Total	-3.910

With mitigation

Mitigating action	Cost of mitigation action	Mitigated %	Net impact post mitigation	Cost savings	Utility	Weight	Mitigation score
1 Monitoring wells	$ 800,000	$ 0.80	$ -	-$ 800,000	-0.032	5.00	-0.16
2 Public campaign	$ 200,000	$ 0.50	$ 528,171	$ 128,171	-0.328	5.00	-1.64
3 Drill second well	$ 150,000	$ 0.60	$ -	-$ 150,000	-0.116	5.00	-0.58
						Total	-2.380

Figure 35 Critical event analysis showing one instance of the Monte Carlo simulation where public opposition occurs but where there is no CO_2 leak or problems with CO_2 injectivity. The @Risk output to the right of the figure displays the probability of a CO_2 leak occurring (which does not occur in this instance) and its estimated cost. The impact to the critical event score with mitigation (bottom) and without mitigation (top) is also shown in the last column on the right of the table. The mitigation options are used to assess tradeoffs incurring between additional costs and reducing the severity or likelihood of critical events.

Mitigation actions come at a cost and thus their default score is slightly less than the 0 associated with the no-event situation. For the example above, the three mitigation actions are meant to reduce the severity or likelihood of the critical event. Extra monitoring wells are employed in the first instance to map the injection of CO_2 and detect any leakage. This is designed to detect any

CO_2 leakage out of the storage reservoir before it reaches the surface and to aid in stopping a leak from spreading but understanding its areal extent in the subsurface. For the public opposition critical event, the mitigation action would be to pursue more public engagement than usual to help prevent any strong opposition that may occur. The third critical event involves difficulties in injecting CO_2 into the storage reservoir at a sufficient speed. Drilling multiple wells may alleviate this problem. DMs can analyse many mitigation actions in response to critical event scenarios to determine both which actions should be taken and how much of that action (e.g. two injection wells or three injection wells).

In the example above, the critical event of strong public opposition reduces the project score by -3.91. If a public outreach campaign had been conducted, then the severity of the event would have been reduced and the score would have only dropped by -1.64. In this scenario in hindsight, it would have been best to conduct the public outreach campaign but not to install extra monitoring wells or to drill a second well. However, this represents just one possible outcome and there is no way of knowing in advance which critical event may occur or which mitigation option to pursue. Therefore we use Monte Carlo simulations to assess all possible outcomes. Monte Carlo simulation can use the utility functions and likelihoods and severity of the critical event analysis to simulate the impacts of the critical events on both project selection and also whether to pursue mitigation options. It can help inform the DM about both the expected outcomes of each mitigation option as well as the full spectrum of possible outcomes.

Inclusion of critical events in the model introduces relationships between the criteria, which may no longer be treated as independent in the assessment. For example, a major CO_2 leak can affect environmental, economic and social criteria. Further research is needed for full-scale CCS project analyses to determine what these relationships are and how they impact the different criteria values. Such critical events can introduce positive and negative feedback effects into the initially independent criteria and allow for a more realistic assessment; however, this adjustment can require substantially more data. For this reason no interdependence was included in this example.

Step 12 involves assessing scenarios to determine how best to implement mitigation actions to reduce the likelihood or severity of possible critical events. Each mitigation action has an impact on some or all of the criteria values, but also incur a cost. Scenarios involving implementing some, or all, of these options to varying degrees could be developed to determine the optimal mitigation strategy to improve the criteria scores, reduce uncertainty and reduce the probability of critical events such as CO_2 leakage. This is an optional step which risk-takers may not choose to pursue, while risk-averse DMs may.

For this example, choosing mitigation options 1 and 2 resulted in the highest expected mean score (see Table 14). Since we have converted the impact of the critical events and mitigation options into utility scores in order to be in comparable units, the calculations are completed within the program and only the scores are shown. Choosing mitigation option 1 alone however produced the highest rated score for 67% of the Monte Carlo iterations. This option did not correspond with the highest expected mean option because the iterations when it was not ranked first had very low scores (i.e. high penalty). This is the result of an absence of mitigation actions to reduce the impact of critical events 2 or 3. The option with the worst potential score was mitigation option 2 combined with option 3, yielding a combined score of -8.01. The option with the highest potential score was to do no mitigation, which corresponds to no critical event happening and no mitigation costs incurred. The variation in possible outcomes between the choices highlights the difficulty in making decisions based only on the mean expected outcome, especially when the mean scores are very similar, as is the case here.

Table 14 Results of mitigation actions showing their mean expected scores, minimum and maximum scores, and what percent of the time they were ranked on the preferred choice. These values represent the results of Monte Carlo simulations of the critical event and mitigation options to evaluate the preferred options. The simulations are based on uncertain criteria, critical event and mitigation data in order to assess all possible scenarios.

	Mitigation 1	Mitigation 2	Mitigation 3	Mitigation 1 & 2	Mitigation 1 & 3	Mitigation 2 & 3	Mitigation 1 & 2 & 3	No Mitigation
Mean score	-0.73	-0.96	-1.14	-0.65	-0.83	-1.06	-0.75	-1.04
Rank	67.1	2.4	0.7	11.9	3.5	0.6	2.8	13.7
Minimum	-7.21	-7.86	-7.91	-5.62	-5.56	-8.01	-3.89	-7.95
Maximum	-0.03	-0.16	-0.15	-0.19	-0.18	-0.31	-0.33	0

The biases of a DM can impact the decisions made as a result of this mitigation analysis, as they may be risk-averse and want to choose the option with the highest minimum score (-3.89), which is to undertake all three mitigation options to avoid extreme negative events and their consequences. A risk-seeking DM may however choose to not use any mitigation actions, as that option could achieve the highest possible maximum score (0) if no critical events occur.

Decision tree analysis is one tool that can be used to model the sequence of decisions and uncertain events, and establish the best option for mitigation actions to limit the impact of potential critical events. The options available to a DM, with each branch representing a choice, are shown in Figure 36. Selecting between Project A and Project B are the first two options along the tree. From there, the next step is to choose between the mitigation options (if any). The branches include the assessed probability distributions developed earlier for each criterion, as well as the uncertainty and impact of the critical events. The score for each mitigation scenario is shown on the right side branches, with the full cumulative project and mitigation score shown on the far right of the tree. The optimal choices with the highest scores in this example are identified with gray shading. A DM can choose mitigation option 1, 2, 3, none, or a combination of the three mitigation options. In this instance of the example Project B has a higher score than Project A and the mitigation strategy with the highest score is a combination of both mitigation options 1 and 2. Once the Monte Carlo simulation is run on the model for several thousand iterations, the options having the highest expected cumulative score are determined. The risk model is developed so that each calculated step in the procedure is linked, so that the Monte Carlo simulation performed in the last step will incorporate all uncertainties in criteria values, critical events and mitigation actions set up at earlier stages of the model.

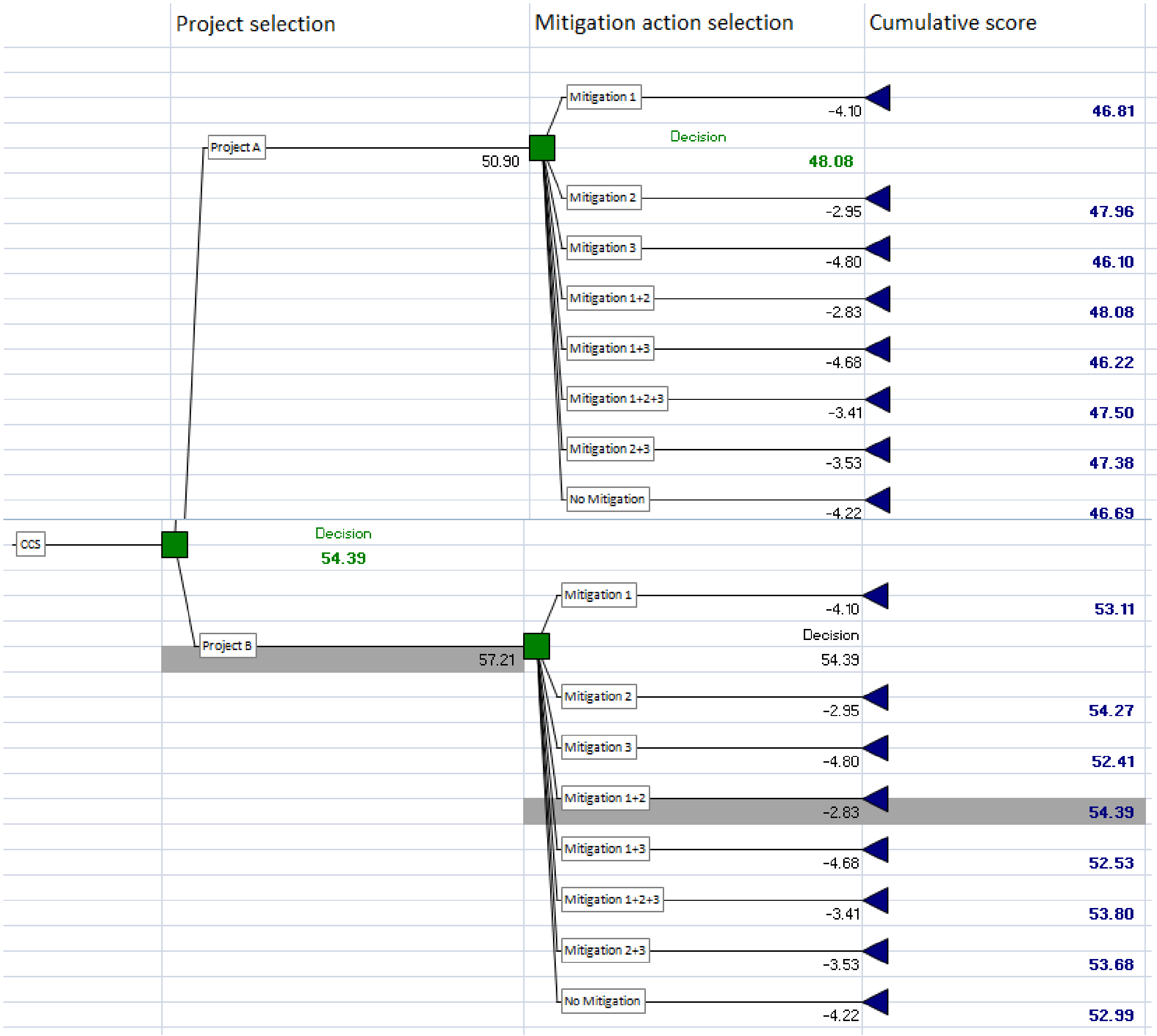


Figure 36 Decision tree showing all possible choices for a DM in the CCS example. The gray shaded cells represent the options with the highest outcome in this instance.

Step 13 is the final phase of the risk assessment procedure, where the overall evaluation and selection of the alternatives (Projects A or B) is made by the DM. Once the DM examines the final probability distributions of scores for the alternatives based on the utility curves, sensitivity analysis, criteria values and critical event analysis, they may choose to change some of their weightings to better reflect their preferences. A DM can also choose to conduct more studies on specific aspects of the projects in order to reduce uncertainty in their data estimates or even to include further criteria, and then rerun the model. The model can also be run iteratively throughout the lifetime of a project as new data becomes available and conditions change.

5.4 CONCLUSION

This model is aimed at high-level CCS decisions, to incorporate many criteria without being so detailed as to be cumbersome, but with sufficient quantitative data to provide meaningful results. CCS decisions are rarely simple and could benefit from more systematic and comprehensive decision analysis such as the proposed MCDA risk assessment model. The model is extremely flexible and can be used as a framework that can be adapted to any complex, comparative decision problem. The criteria chosen may be different depending on the specific objectives of the decision maker. CCS is unique because of its complexity, rapidly evolving technology, long time horizons, varied impacts and different stakeholders, and the criteria chosen should reflect this. This article proposes certain criteria that do take important characteristics of CCS into account; however, these criteria can be adapted and substituted as desired.

This model does not prescribe a particular decision for a DM. Instead, it should be utilised to transparently and comprehensively assess a complex decision. As the model is based on a DM's preferences, there is no right or wrong choice. Each of the steps provides more information in a meaningful way so that a DM can better understand the benefits and drawbacks of each alternative. The model produces much of the same statistical information found in other assessments, but does so in a visual manner and incorporates a series of important elements such as critical event analysis, which help the DM understand how the projects respond under many different possible scenarios.

As more CCS projects are being considered, it is increasingly important to have a transparent and quantitative MCDA to aid a DM and avoid future roadblocks. As many people distrust CCS, the openness and simplicity of the model demonstrate the benefits of CCS and allow the technology to be compared with other climate change mitigation options. The MCDA framework proposed above allows for flexibility in the criteria assessed, while recommending a set of frequently used criteria that are found in many CCS assessment studies, although not necessarily together (Choptiany *et al.,* in review). It includes sensitivity analysis and Monte Carlo simulation, recognizing and addressing the high-level of uncertainty associated with CCS projects.

The MCDA risk model can be used for any high-level comparative study and will benefit from further case studies to expand and refine it. The model can easily accommodate multiple DMs, thus allowing for a more interactive engagement process with stakeholders, including the public. For large-scale competitions for government support, the model can also be used to provide a transparent assessment method by which to choose between competing projects. Within companies and utilities, detailed assessments such as site selection, or even whether to pursue CCS or not, can be achieved using this methodology with minor modifications to the structure and always selecting decision-specific criteria. Finally, consistency, flexibility, transparency and the ability to compare between projects will allow for a better understanding of CCS projects worldwide including why some are halted while others are moving forward (IEAGHG, 2010). Ultimately, this model provides sound backing for any CCS decision.

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CHAPTER 6

A RISK FRAMEWORK FOR CARBON CAPTURE AND STORAGE USING A MULTI-CRITERIA DECISION ANALYSIS APPROACH: CANADIAN CASE STUDY

This chapter builds upon Chapter 5 by more fully developing and demonstrating the decision analysis model for CCS decisions. The authors developed a pilot study using data collected in Chapter 4 to create three realistic CCS case studies. Representative criteria were also used to address environmental, social, economic and engineering factors. The pilot study, as well as the risk model, was presented to CCS experts in Alberta for comment and expert opinion. The experts were asked to review the case studies and provide their opinions on the relative importance of the criteria to a project selection decision. Using responses from the experts, Monte Carlo simulations were run to simulate CCS decision scenarios. The responses from the experts were categorised into different groups to run the simulations, with sensitivity analysis being conducted to address uncertainty. The results of this pilot study demonstrate the benefits of the CCS risk model. The paper was submitted to the Journal of Greenhouse Gas Control. Dr. Ronald Pelot is a co-author on this article. In this chapter, references to appendices are replaced by references to the thesis in the version that is submitted to the journal.

6.1 ABSTRACT

Carbon capture and storage (CCS) is a technology used to mitigate anthropogenic climate change through the removal of CO_2 emissions from fossil-fuelled power plants. CCS is a relatively new, large-scale technology with potentially large geographical and temporal impacts. There are large uncertainties surrounding CCS with respect to costs, impacts, and risks as well as many options and factors to consider. Due to this complexity and uncertainty, CCS decision makers could benefit from a holistic framework with which to compare projects on many heterogeneous criteria. The authors developed a risk assessment and decision analysis framework using multi-criteria decision analysis methods to better understand CCS risks and select between project alternatives. Criteria were chosen from environmental, social, economic and engineering fields to incorporate the important factors of CCS. The model incorporates utility, preferences, thresholds, decision trees, Monte Carlo simulation, critical events and sensitivity analysis. Two case studies and one reference case were developed for a pilot study to demonstrate the model's utility for making complex choices between alternatives. The pilot study included the input of CCS experts from industry, research groups, environmental NGOs, and government, who provided weights for the criteria, representing the criteria's relative importance to CCS decisions. The experts' weights were used to run Monte Carlo simulations as part of the model in order to compare preferences between expert groups. The authors found that there was a wide range in opinion and confidence about the criteria across the CCS experts, which resulted in experts choosing different case studies, further demonstrating the need for comprehensive decision assessments.

6.2 INTRODUCTION

Climate change is one of the most serious threats facing humankind (Rackley, 2010). Carbon Capture and Storage (CCS) is a new suite of technologies with the goal of mitigating climate change by capturing and storing CO_2, in geological reservoirs. The Intergovernmental Panel on Climate Change (IPCC) states that CCS is one of several options needed in the "portfolio of mitigation actions for stabilization of atmospheric greenhouse gas concentrations" (IPCC, 2005). CCS is the process of separating CO_2 (usually from the flue-gas stream of a fossil-fuelled power plant), compressing the gas and transporting it to, and injecting it into, a geological reservoir for storage (Natural Resources Canada, 2006). The injected CO_2 gas is intended to remain permanently stored under pressure in the geological formation, although there is a small possibility of leakage out of the reservoir. CCS refers to a process and not a single technology, as there are many different technologies that can achieve these actions (Meadowcroft and Langhelle, 2009).

The efficacy of individual stages of the CCS process (CO_2 capture and separation, transport, and geological storage) has been proven with many commercial projects over the last few decades (Havercroft *et al.,* 2011). CCS incorporates these individual stages into one process on a large scale, which creates new challenges. Several pilot and demonstration plants exist; however, few commercial scale projects using all three stages have been developed to date (MIT, nd; IPCC, 2005, CO2CRC, 2010). The lack of full-scale, integrated CCS projects is in part due to concerns about high costs, uncertain regulatory regimes, and public opposition (Carbon Capture Journal, 2010; Reuters, 2011, Anderson *et al.,* 2012). There are many complex aspects of CCS that require decisions on how best to develop CCS projects. CCS decision analysis could benefit from a holistic consideration of environmental, social, engineering and economic factors, in order to better understand the relative risks associated with CCS and increase the development of CCS (Choptiany *et al.,* in review).

Multi-criteria decision analysis (MCDA) is a method for making decisions that incorporate multiple aspects of decision making into one analysis. MCDA methods use criteria with different units to assess outcomes that can be both quantitative and qualitative (Cavallero, 2009). MCDAs amalgamate criteria and use decision makers' (DMs') weights to represent the relative importance of criteria to their decisions. This process places criteria on the same scale (of utility or usefulness) which DMs can compare. MCDAs have become a popular tool for assessing complex problems and are increasingly being used to assess large-scale energy options (Viebahn *et al.,* 2007; Pehnt and Henkel, 2009: Wang *et al*., 2009).

The authors previously developed a risk assessment model using a MCDA approach to evaluate large-scale CCS project risks and compare alternatives (Choptiany and Pelot, in review). The model framework includes a procedure for assessing these complex, large-scale problems. DMs can modify the individual aspects of the procedure to suit their specific decision problem. In order to demonstrate the utility of the model in making DM-specific, complex decisions, a pilot study was conducted in which two CCS case studies were developed (Projects A and B), based upon a combination of project-specific data, peer-reviewed literature and expert opinion. A further reference case was developed using peer-reviewed data only, in order to provide context to the two case studies. The reference case was developed to represent a typical CCS project using the mean of all the criteria data collected, which also serves to highlight the differences in Projects A and B which are more site-specific. CCS experts were then interviewed to obtain their preferences and simulate a decision scenario. The detailed data allowed the experts consulted to consider real world options, but are not representative of any specific CCS projects.

Experts in CCS were chosen from government agencies, research groups, environmental non-governmental organisations (ENGOs) and industry to elicit their opinions of the relative importance CCS decision criteria for this pilot study. Details about the case study projects and the MCDA model were presented to the experts to explore. The authors did not interview lay-persons with respect to CCS, as experts were needed to understand the wide variety of impacts specific to CCS; however, participants were not necessarily experts in each criterion area, which was reflected in their self-assessed confidence scores for each criterion.

Using criterion weights collected from the CCS experts, the three case studies were compared in the MCDA model to determine which case study project was preferred. Monte Carlo simulation was employed to take into account uncertainty of the data and the expert opinions for each project using a probabilistic assessment. A one-way sensitivity analysis was also performed for each criterion. Potential critical negative events and subsequent mitigation options were also explored to supplement the sensitivity analysis and introduce interdependence among some of the factors. The pilot study demonstrates the utility of this unique CCS-specific risk model by exploring the factors that influence decision making. The authors used the pilot study to assess the need for a holistic and comprehensive assessment of CCS decisions and whether intricacies within complex decision processes can significantly impact project selection. The study also explores which aspects of CCS projects have the largest risks, explores how project risk could be reduced, and demonstrates how different groups consider risks and rank the case study projects. The level of understanding of CCS criteria and confidence among CCS experts for their opinions was also explored using scenarios in the model.

The results of the pilot study will be demonstrated in this article in the following manner: the first section (6.3) outlines the theory and procedure for performing the risk model. The next section (6.4) outlines the steps in the pilot project and the results of the expert opinion simulations. The pilot study results are also described and analysed here, with a focus on the relevance and importance of each model element. CCS expert comments on the model design and applicability of the model for other CCS decisions are discussed in section 6.5.

6.3 RISK MODEL PROCEDURE AND METHODS

The pilot study aimed to validate the authors' risk assessment model, which uses a MCDA approach for assessing CCS decisions (Choptiany and Pelot, in review). Three case studies were developed and expert CCS opinions were collected in a proxy 'decision' scenario. The model uses aspects of MCDA methods, but is not based upon any existing models. The full general procedure for the CCS model is shown in Figure 37 and described in more detail in Choptiany and Pelot (in review). The CCS expert survey portion of the pilot study described below in this article corresponds with Step 7 in this procedure. The other steps in this assessment were conducted prior to, and after, CCS expert weights were collected in the pilot study and reflect Steps 6-9. Each of the model procedure steps are described below using the CCS case studies for the decision problem.

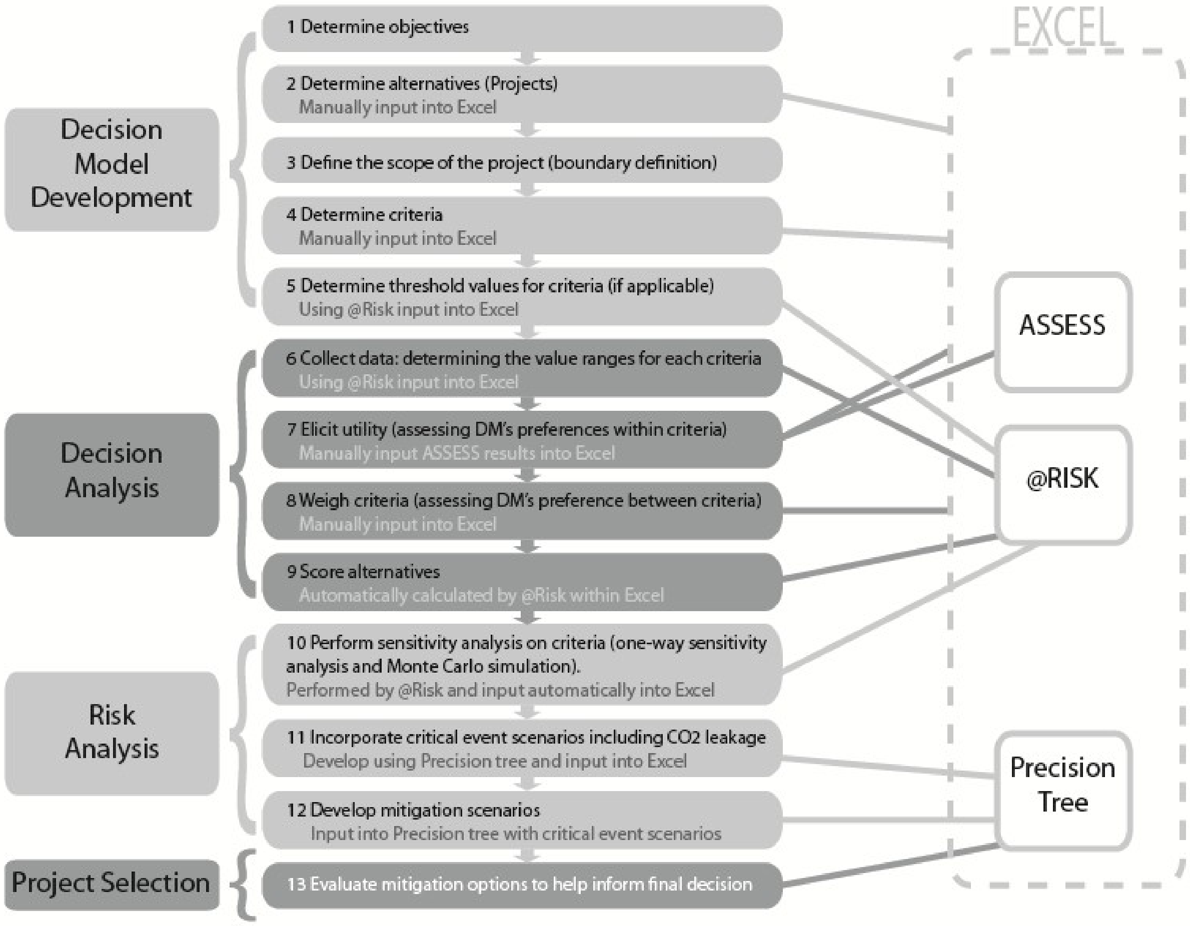

Figure 37 Procedure for MCDA CCS risk assessment model showing the 13 Steps divided into four main areas (decision model development, decision analysis, risk analysis, and project selection). The model must be performed in order but it can be an iterative process. The model uses four software programs (Excel, ASSESS, @Risk and Precision Tree). The software involved with each step is shown to the right of the graph. Excel is the primary user interface with @Risk and Precision Tree integrated directly, while ASSESS outputs have to be manually inputted into the system (Choptiany and Pelot, in review).

6.3.1 Decision Model Development

The objective of the pilot study (Step 1) was to choose between three CCS case studies using input from CCS experts as proxies for CCS decision makers. The three alternative case studies (CCS projects) developed in Step 2 each represented a new post-combustion, coal-fuelled CCS power plant to be built in the near future on a Greenfield site in a rural setting. The boundaries of the assessment (project scope) are shown in Table 15 (Step 3). The CCS plants were assumed to all last for 30 years and to transport and store 4 MT of CO_2 per year. Due to the large quantity of CO_2 to be stored and relatively small storage reservoirs, each project required several reservoirs at each geological storage site to contain the total CO_2 injected over 30 years (~120 MT CO_2). No carbon tax or credit was applied to the CO_2 stored, however revenue from enhanced oil recovery (EOR) was considered due to its current inclusion in many CCS projects, which helps to offset costs.

Table 15 CCS project parameters derived from a literature review, project specific data, and expert opinion

Parameter	Project A	Project B	Reference case
Fuel source	Coal	Coal	Coal
Capture technology	Post-combustion technology 1	Post-combustion technology 2	Post-combustion technology 3
Power plant output (MW)	500	500	500
CO_2 produced at power plant	4 million tonnes	4 million tonnes	4 million tonnes
Transportation distance	100km	150km	50km
Storage type	Depleted oil field 1	Depleted oil field 2	Depleted oil field 3
Storage reservoir capacity	30 million tonnes	20 million tonnes	25 million tonnes
Storage reservoirs required	4	7	5
Project lifespan	30 years	30 years	30 years
Location[11]	Alberta	Saskatchewan	Europe

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[11] The social criteria data were extracted from surveys conducted in Alberta, Saskatchewan and Europe.

The model uses a set of CCS-specific criteria (or attributes) by which the decisions (project options) are compared (see Table 16). The criteria were chosen in Step 4, based on availability and completeness of data, and frequency of use in other studies, and were adapted from a criteria list in Choptiany *et al.,* (in review). As the model demonstration is considering the three case studies holistically and at a high-level, the criteria were chosen to reflect this breadth, and as a consequence may exhibit some interdependencies. Each criterion can have risks associated with it, arising from potential deviations (positive or negative) from its expected value.

Table 16 Criteria used in the MCDA and risk assessment framework (adapted from Choptiany *et al.,* in review)

Environmental	**Social**	**Economic**	**Engineering**
Global Warming Potential GWP): % reduction in (gCO_2 e/kWh)	Public Perception (0-1) Higher is better	Incremental Capital Cost ($) in millions	CO_2 Capture Efficiency (%)
Photochemical Ozone Creation Potential (POCP): % reduction in (gC_2H_4e/kWh)	Knowledge of CCS (0-1) Higher is better	Capture Cost ($/$tCO_2$)	Storage Reservoir ($MtCO_2$)
Eutrophication Potential (EP): % reduction in (gPO_4^{3-} e/kWh)	Perceived Impact on Health (0-1) Higher is better	Transportation Cost ($/$tCO_2$)	EOR Revenue ($/$tCO_2$)
Acidification Potential (AP): % reduction in (gSO_2 e/kWh)	Perceived Impact on Climate Change (0-1) Higher is better	Storage Cost ($/$tCO_2$)	
Human Toxicity Potential (HTP): % reduction in (Years of life lost/kWh)	Perceived Impact on Other Technologies (0-1) Higher is better	Incremental Operating Cost ($/year) millions	
		Incremental Cost of Electricity ($/kWh)	

Thresholds can be used where participants are able to set acceptability limits for a criterion (see column 7 in Table 17 for thresholds used in this study). Thresholds can either be self-imposed (often due to economic constraints) or imposed externally through regulations on emissions or project requirements. Beyond a threshold value, a criterion is considered unacceptable (Munier, 2004). This adds another tool by which to assess the decisions. From the decision analysis outputs, DMs are able to see the likelihood that the CCS projects exceeded the thresholds on a given criterion. In this example, thresholds were determined in consultation with industry experts prior to administering the survey in the pilot study. Thus, thresholds were only set once, hence not individualized for each surveyed expert, and were just used to provide more contextual information on each criterion.

6.3.2 Decision Analysis

The CCS model incorporates components of MCDA methods including utility curves, preferences, decision trees, Monte Carlo simulation, and sensitivity analysis. Each will be discussed in turn, corresponding to Steps 6 through 9 of the model procedure.

For Step 6, data were collected from published journal articles, public opinion surveys (IPAC-CO_2, 2011 for the Canadian case studies; Eurobarometer, 2010 for the European reference case) and from project-specific data from two CCS projects described in Choptiany *et al., (*in review). The breadth of data enabled probability density functions to be created for each criterion's possible values. Expert opinion was relied upon to ensure that the selected data were internally consistent and realistically represented the three CCS case studies.

For Step 7 of this study, utility curves were developed with ASSESS, a software program that uses a series of questions in the form of probability lotteries to elicit DMs' preferences and to find indifference points (Delquie, 2008 and described in more detail in Choptiany and Pelot*,* in review). Using the collected criteria data, the minimum and maximum values for each criterion are determined with the best value being assigned a 1 and the worst a 0. The minimum and maximum value for each criterion represent the best and worst possible scores that a project could have on a criterion and also sets the boundary of the assessment. To elicit utility curves, DMs were given a choice between a known criterion value and a probability of either a low or high value (e.g. the choice between a 100% chance of encountering 20 Mt of CO_2 storage potential, versus a 30% chance of 30 Mt of CO_2 storage potential and 70% chance of 5 Mt CO_2 storage potential). After each choice, the scenario conditions are varied (either the likelihood or the values). Eventually, the scenario conditions will represent a choice where the DM is indifferent between the choices. The point at which the DM is indifferent between the choices becomes a point on the graph (see Figure 38 for a sample utility curve for CO_2 storage potential and column 'utility' in Table 17). Once sufficient data points are collected, they are plotted and a curve fitted. From the data, an equation of the curve (the utility function) is created (see 'utility function' in Table 17). The equation of the curve can be used to estimate DMs' preferences anywhere along a criterion's feasible range of values.

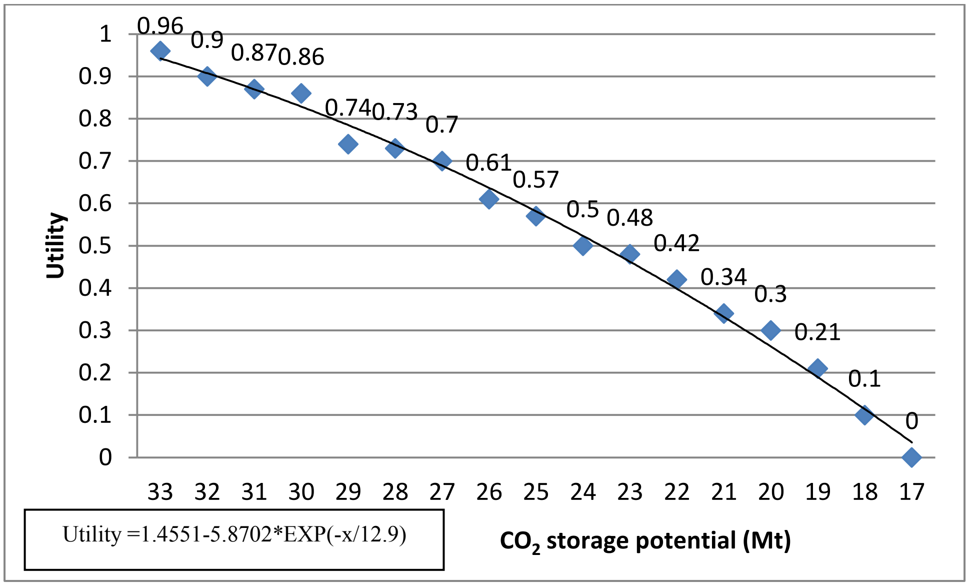

Figure 38 Utility curve for CO_2 storage reservoir potential showing a higher utility for more CO_2 storage potential

Table 17 Risk model database for Project A. All numerical data (in normal font) is specific to Project A, whereas all columns, rows, headings, criteria, criteria units, and utility functions are common to all projects and shown in bold.

Area	Criteria	Criteria Value	Units	Utility	Weights	Thresholds	Criteria Score	Normalised	Utility function
Environmental	**GWP**	0.529	**% reduction in gCO_2-e/kWh**	0.172	12.55	≥0.10	2.16	2.16	**(-)0.2872+0.11*exp(-x/-0.37)**
	POCP	-0.017	**% reduction in gC_2H_4-e/kWh**	0.180	2.94	≥0.05	0.53	0.53	**(-)0.9808+1.2398*exp(-x/-0.26)**
	EP	-0.123	**% reduction in PO_4^{3-}e/kWh**	0.325	2.63	≥0.00	0.85	0.85	**1.2219-0.5485*exp(-x/0.25)**
	AP	-1.105	**% reduction in gSO_2-e/kWh**	0.224	3.22	≥-0.10	0.72	0.72	**(-)0.4323+0.914*exp(-x/-3.34)**
	HTP	-0.04	**% reduction in Years of life lost**	0.495	3.99	≥-0.05	1.98	1.98	**(-)0.484+1.0304*exp(-x/-0.77)**
Social	**Public perception**	0.300	**0-1**	0.402	6.34	≥0.30	2.55	2.55	**1.6566-1.6566*exp(-x/1.08)**
	Knowledge of CCS	0.201	**0-1**	0.136	3.34	≥0.30	0.45	0.45	**(-)0.6793+0.6793*exp(-x/-1.1)**
	Perceived health impact	0.093	**0-1**	0.060	3.89	≥0.30	0.23	0.23	**(-)0.6793+0.6793*exp(-x/-1.1)**
	Climate change	0.452	**0-1**	0.345	3.11	≥0.30	1.07	1.07	**(-)0.6793+0.6793*exp(-x/-1.1)**
	Impact on other technologies	0.341	**0-1**	0.247	2.05	≥0.30	0.50	0.50	**(-)0.6793+0.6793*exp(-x/-1.1)**
Economic	**Capital cost**	$1,602	**$/tCO_2$**	0.834	8.75	≤$1,600	7.30	7.30	**(-)2.3531+3.3774* exp(-x/27672)**
	Capture cost	$ 54.4	**$/tCO_2$**	0.296	11.68	≤$60	3.45	3.45	**(-)1.8589+3.1837* exp(-x/139.39)**
	Transport cost	$ 1.1	**$/tCO_2$**	0.921	4.20	≤$4	3.87	3.87	**1.7736-0.77*exp(-x/-10.79)**
	Storage cost	$ 2.2	**$/tCO_2$**	0.921	4.61	≤$5	4.25	4.25	**7.4729-6.3314*exp(-x/-63.34)**
	Operating cost	$ 109.0	**$/kWh/y**	0.588	6.00	≤$130	3.53	3.52	**(-)1.7261+2.9014*exp(-x/481.38)**
	Cost of electricity	$ 0.06	**$/ kWh**	0.915	6.11	≤$0.06	5.59	5.59	**(-)4.1615+5.3887*exp(-x/0.93)**
Engineering	**CO_2 Capture effectiveness**	88.21	**% CO_2 captured**	0.556	4.20	≥70%	2.34	2.34	**(-)1.7494+0.3139* exp(-x/-44.24)**
	Storage potential	29	**Mt**	0.858	4.07	≥20	3.49	3.49	**1.4551-5.8702*exp(-x/12.9)**
	EOR revenue	$ 54	**$**	0.968	6.36	≥$20.00	6.16	6.15	**1.1429-7.4264*exp(-x/14.43)**
					100	Total	51.03	51.01	

Monte Carlo simulation was used to assess all possible combinations of values for the criteria based on the probability distributions of the data using the software @Risk by Palisade in this pilot study (Palisade, 2012). Monte Carlo simulation is a method of simulation in which the probability distributions of criteria values are randomly sampled to generate data (von Neumann, 1944, Kalos and Whitlock, 2008). This produces a holistic picture of the possible outcomes of complex multi-input problems which are used in the model during Steps 9, 10 and 13. Using the utility functions for each criterion developed in the previous step, Monte Carlo simulations produce probability distributions of DMs' preferences for all possible outcomes for each project's criterion values. The criterion scores are then summed to give an overall project score (see the criteria score column in Table 17). The databases for each project use the same utility curves, weights, criteria, units and possibly thresholds (which could be different depending on local conditions such as environmental limits in different locations); the only part that is different between these project databases is their input data which is characteristic of the individual projects. Thus, the different criteria values for each project result in different scores, which reflect the individual DMs' preferences.

As Monte Carlo simulations are run in Step 8, each iteration generates a value for each criterion drawn from the criterion's probability distribution of values (Ho and Pike, 1998). A utility value is needed for every generated criterion value to create a criterion score. Since we have a utility curve for each criterion, the utility for any criterion value can be calculated and the simulation can proceed with the simulation without further user input. Utility curves reflect how DMs value each criterion under all possible scenarios from best to worst cases. Utility curves can either represent one DMs' preferences or can be the amalgamation of several DMs. For this study, one utility curve is used for all DMs. Utility curves also enable criteria with different units, often comprising both quantitative and qualitative data, to be compared on the same scale (Clemen, 1996). Utility curves may reveal a DM's risk attitude, as a concave curve implies a risk-averse preference pattern and a convex curve implies risk-seeking behaviour (Samson, 1988).

For Step 8, CCS experts were asked to give a relative weighting to each of the criteria based upon how important they feel the criterion is to a CCS project selection decision (see column 'weights' in Table 17). Each criterion therefore has both a utility function (Step 7) and unique DM-specific (or DM amalgamated) weight. For each iteration of the Monte Carlo simulation, a project's criterion value will thus have a specific utility. The utility value is multiplied by the weight of that criterion to give a criterion score. Each project's criteria are summed to give a project score. Once a number of iterations are run, a probability distribution of a project's scores is created, which can be compared with other projects' criteria (see Figure 39).

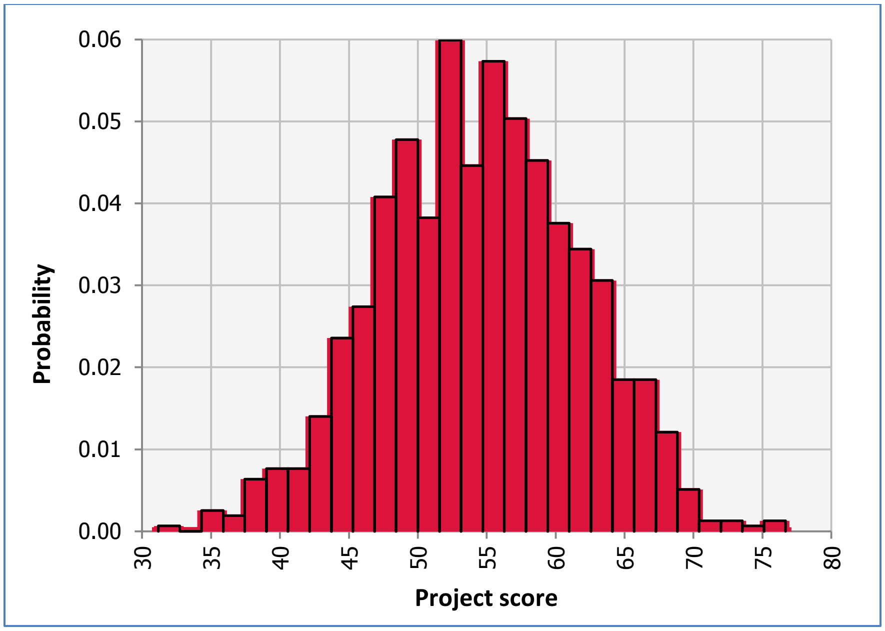

Figure 39 Probability distribution of Project A's overall score out of a possible maximum of 100

The criteria have maximum utility values of 1.0 respectively and are multiplied by the weights to produce a criteria score (which cumulatively sum to 100), so that each project can have a maximum score of 100. The projects' scores in each decision analysis are dependent on the criteria chosen, utility curves, and collective weights assigned by the DMs. A project's score is therefore relative only to the other projects used within the same decision analysis framework and do not represent an absolute score. A wide variety of projects can be compared using this CCS model, however the decision analysis design would need to be tailored to each situation to ensure that each project is adequately assessed.

In addition, a one-way sensitivity analysis was conducted in Step 10 by varying the criteria values to see which criteria have the largest influence on the decisions. The criteria values were varied in a stepwise fashion both positively and negatively by three, five, seven and ten percent around each criterion's mean value for each of the three projects. Another common method is to vary the criteria values by one or two standard deviations from their means, which takes into account the varying levels of uncertainty between the criteria. For example, criteria values that are expected to vary by ±200% on a project would not be well represented by a sensitivity analysis that adjusted the criteria values by ±10%. It would be better in this instance to vary the criterion by one or two standard deviations away from the criterion's mean value to effectively demonstrate the potentially large impact this criterion could have on a project. During the sensitivity analysis we ascertained the degree of change in criterion values required before CCS project selection was changed.

The last steps in the risk analysis portion of this MCDA model procedure are to develop scenarios for possible critical events (Step 11) and mitigation measures (Step 12) to address them. Based on discussions with CCS experts prior to and separately from the pilot study, possible negative critical events and mitigation scenarios were developed. Three major negative events were considered as possible threats to the success of the CCS projects in the pilot study. These are specific events, beyond the normal operating conditions expected at a CCS project, that could have a significant impact on a project's viability. These included a CO_2 leak, the storage location(s) not accommodating expected CO_2 injection rates, and public perception drastically worsening due to a CO_2 leak at a CCS project elsewhere (see Table 18). For the instance shown in Table 19, no critical event occurred and thus their impacts were zero. Each scenario was developed with simple triangular probability distributions (due to limited data) of the likelihood of critical events occurring, as well as their severity in terms of cost. Mitigation costs and impacts, shown to the right of the table, are explained below.

Table 18 Critical event analysis table. In this iteration no critical event occurred whereas a critical event does occur in Table 19

Critical event	Mitigation option	Event occurred	Score without mitigation	Score with mitigation	Event cost (thousands)	$ saved (thousands)
CO_2 leak	**Monitoring wells**	No	0	-0.03	$ 0	-$ 700
Public opposition	**Public campaign**	No	0	-0.16	$ 0	-$ 20
Injection rate too low	**Drill second well**	No	0	-0.15	$ 0	-$ 500

For this study, each possible critical event was given a weight of 5, which is multiplied by the utility curve to produce a critical event score which is added to each project's overall score. The utility curves range from 0 for the best score to -1 for the worst event. The critical event weights were chosen using expert opinion and can be adjusted by the DM to reflect their possible impact on the viability of the project (see Choptiany and Pelot, in review, for a further explanation of the process). The events, (which had both a probability of occurrence and of severity if it did occur), were converted from impacts (in terms of cost) into utility values. The events would then reduce the project score by an amount determined by a separate utility function specific to the event type and the severity of the event for this specific scenario (in this example the worst penalty is -5.0). The probability distribution of severity is used to simulate the possibility of varying degrees of events such as a small or large CO_2 leak.

In conjunction with the critical events, three mitigation options were developed that could be put in place prior to the project's commencement (see Choptiany and Pelot, in review). The mitigation actions incur an added cost but reduce the severity of the event if it does occur (see Table 19). The final columns in Tables 21 and 22 display the cost of the critical event as well as the potential savings as a result of implementing the mitigation action if an event does occur. These values will vary depending on the severity of the critical event. Mitigation actions can be thought of as insurance policies where, if no critical event occurs, they would not be needed, but if it does, they would limit the impact of the critical event. Therefore, there is a trade-off between limiting the potential event by incurring a cost, and foregoing the mitigation cost at the risk of a more severe event if an event does occur. Although only three critical events were considered in this study, many more could be included in future studies if the situation warranted them. Competing mitigation actions can also be compared.

Table 19 Critical event table. In this case a negative event did occur (severe public opposition to the project)

	Mitigation action	**Event occurred**	**Score without mitigation**	**Score with mitigation**	**Event cost (thousands)**	**$ saved (thousands)**
CO_2 Leak	**Monitoring wells**	No	0	-0.03	$ 0	-$ 700
Public opposition	**Public campaign**	Yes	-4.38	-1.93	$ 675	$ 463
Injection rate too low	**Drill second well**	No	0	-0.15	$ 0	-$ 500

Prior to including critical event analysis, the assessment method assumes that the criteria are independent. Once a critical event is introduced into the assessment, it could potentially impact multiple criteria. For instance, a CO_2 leak could impact GWP, HTP, all social criteria and increase the cost of storing subsequent CO_2 thus linking these criteria together. Critical event analysis is more speculative than other aspects of the assessment and can be considered as an extreme sensitivity analysis, based on possible severe consequences. Bow-tie-analysis, a method used to understand the causes and consequences of hazards and negative events occurring (and so named for its shape which is composed of many causes culminating in one event which then can cause many different effects) (IEA GHG, 2009), can also be used to develop possible critical events, estimates of their likelihood and severity, and to identify ways to prevent them.

6.4 CCS PILOT STUDY

Once the objectives and project alternatives were determined, scope defined, criteria selected, data collected, and utility elicited (Steps 1 through 6), expert-specific weights for the criteria were determined. To populate the model with realistic criteria weights, CCS experts were enlisted for the pilot study. Researchers at *Alberta Innovates: Technology Futures* (AITF) identified 40 CCS experts from industry, research organizations, ENGOs and provincial governmental departments. Those CCS experts who agreed to participate in the study were provided with a summary sheet to provide context to the project and outline their tasks (see Appendices 3B, 3C and 3D). The summary sheet described the study, each of the criteria used in the model, and provided representative values for the three projects on all the criteria (see Tables 18 and 19). After reading the summary sheet, participants were asked to watch a short video demonstrating a simplified version of the model, showing the model methodology and how DMs' weights would be incorporated (see Appendix 3C for a link to the video). The video helped participants understand the probabilistic nature of the model; although all the data appear to be static when shown on paper, they are associated with probability density functions and thus each iteration of the simulation produces different results.

Between May 28th and July 12th 2012, as part of the pilot study to demonstrate the model, 24 CCS experts from different fields were interviewed and asked to fill out a survey while 16 other CCS experts were interviewed and provided feedback but did not complete the survey (see Table 20 for the number of experts within each group). Interviews lasted approximately 1 hour and began by addressing any participant questions regarding the data sheet that was provided to give contextual information to the survey (see Appendix 3D), the model or how to complete the survey. Participants were also asked about the overall usefulness of the model, whether any criteria were extraneous or whether any further criteria should have been included. All responses were kept anonymous. The participants' responses were grouped according to whether the experts came from industry, ENGOs, government, or research groups. Participants chose to fill out the survey either prior to the interview, during the interview or afterwards. Interviews were conducted either in person or via telephone. Interviews were conducted in one-on-one settings or in groups depending on participants' preferences and schedule. Preference was given to one-on-one in-person interviews whenever possible. Group interviews were designed to still ensure anonymous survey responses of individual expert weightings, however participants were permitted to ask each other questions and to learn from questions that others asked of the study designers. Participants were not permitted to change their responses after submitting their weights and confidence levels.

Table 20 Number of CCS experts within each group

Group	Industry	Research	Environment	Government	Total
# of experts	7	5	5	7	24

Participants were given a hypothetical situation in which they were the primary DM for a large energy company and were required to choose a CCS project from the three case studies (Project A, Project B and Reference case). Using the data sheet as context, the experts were asked to assign weights to each criterion based on their perception of the importance of the criteria to their project selection decision (see Table 21 for the economic criteria used by the experts to input their criteria weights and confidence levels). Participants were given 100 points to allocate between the criteria. The only requirements were that each criterion weight must be between zero and 100 and all 19 criteria weights must sum to 100. Participants were also asked to assign a confidence value to each criterion weighting based upon their expertise in each area. The confidence rankings ranged from 1 to 5 with a higher number representing greater confidence. This enabled participants to complete the survey despite not being an expert in each criterion area. Having participants input relative weightings for the criteria allowed for a personalized decision analysis by representing the participants' individual preferences.

Table 21 Sample expert weights and confidence level for economic criteria and reference criteria values for each project. Weights and confidence levels for the social, environmental and engineering criteria were also recorded.

Economic	**Project**				
Criteria	**Project A**	**Project B**	**Reference case**	**Weight**	**Confidence (1-5)**
Incremental Capital Cost ($) in millions	1,500	1,650	1,350	15	5
Capture Cost ($/t$CO_2$)	49	54	44	7	4
Transportation Cost ($/t$CO_2$)	1.06	1.33	.78	4	4
Storage Cost ($/t$CO_2$)	2.16	3.42	2.58	3	3
Incremental Operating Cost ($/year) millions	104	115	93	4	4
Incremental Cost of Electricity ($/kWh)	0.0486	0.050	0.0498	6	3

Due to the small sample size and the use of representative case studies, implications derived from the results should not be extrapolated to assume that one project is necessarily superior to another.

6.4.1 CCS Experts' Criteria Weights

Once the survey portion of the pilot study was completed, the data were compiled and analyzed. The data were organized by the expertise of the CCS participants as well as by the level of confidence in their responses and by type of criterion. The data was then entered into the MCDA risk model to simulate DMs performing the decision analysis to select a CCS project from the three available options.

The minimum, maximum, and mean for each criterion weight is shown in Figure 40 for all 24 experts. Over all of the CCS experts, the criterion with the highest weight was capture cost with an assigned weight of 40, followed by GWP (39), capital cost (25) then cost of electricity (22). Almost every criterion had at least once CCS expert assign it a weight of zero, therefore their ranges were often the same as their maximum value. The criteria with the highest mean weights were GWP (12.55), capture cost (11.68), capital cost (8.75), while the lowest mean weighted criteria were perceived impact on other technologies (2.05), acidification potential (2.63) and eutrophication potential (2.94).

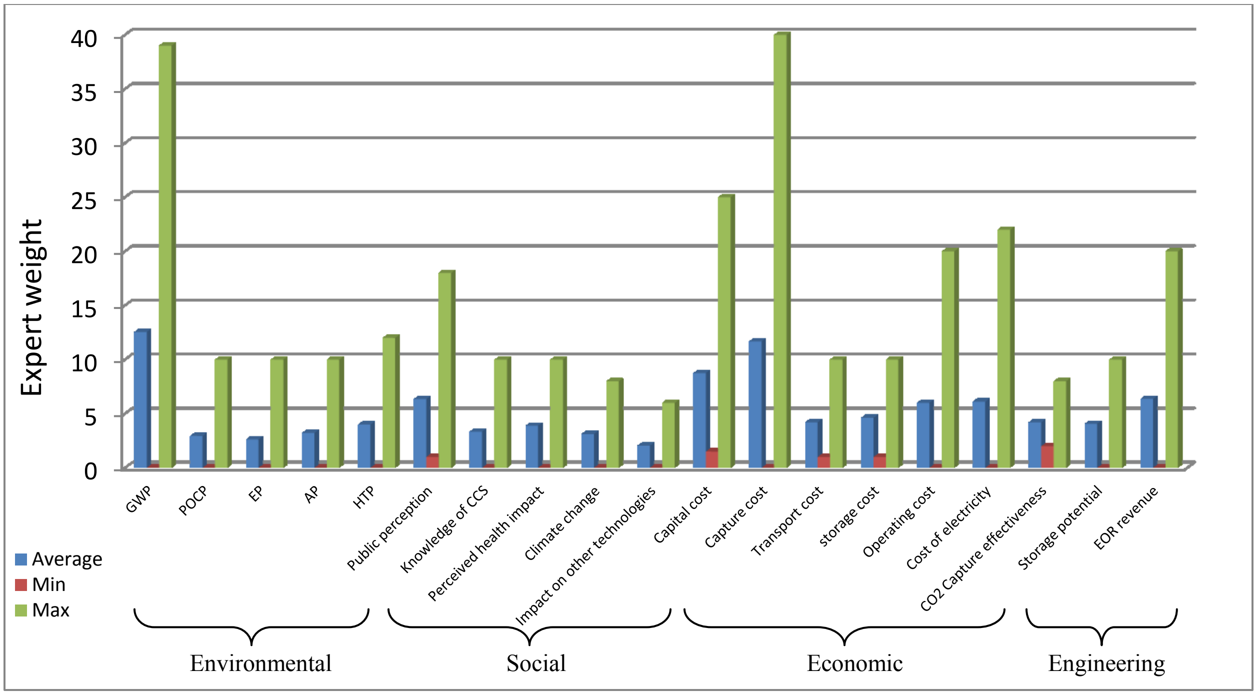

Figure 40 Aggregated CCS expert criteria weights organized into environmental, social, economic and engineering categories

The criteria were organised into environmental, social, economic and engineering categories. This categorization provided a visualisation of the criteria to make weighing them easier but did not impact the project rankings as each criterion was considered independently. The minimum, maximum, and mean of criteria weights, separated into the four CCS expert groups are shown in Table 22. Each group shows the same general pattern with high criteria weights for GWP, Capture cost, and Capital cost, however there are strong differences in the relative weights for the criteria between the groups, indicating substantial differences between expert preferences.

Table 22 CCS expert responses for criteria weights. Bolded data represent the maximum weight for each criterion. The minimum criteria weights are shown in light grey.

		Environmental					**Social**					**Economic**						**Engineering**		
CCS expert group		Global Warming Potential	POCP	Eutrophication potential	Acidification potential	Human Toxicity potential	Public perception	Knowledge of CCS	Perceived health impact	Climate change	Impact on other technologies	Capital cost	Capture cost	Transport cost	storage cost	Operating cost	Cost of electricity	CO_2 Capture effectiveness	Storage potential	Carbon credit/ EOR
Industry	1	15	1	1	2	1	10	1	1	1	2	2	24	1	1	2	15	5	8	7
	2	10	0	0	0	1	4	3	4	3	0	12	12	6	6	12	12	3	**10**	2
	3	3	3	3	3	3	5	0	0	0	0	20	25	5	**10**	0	0	5	5	10
	4	3	2	2	2	3	7	5	5	5	3	7	7	7	7	10	10	5	3	7
	5	36	1	1	1	1	1	5	8	3	3	8	7	2	2	5	6	6	0	4
	6	4	0	0	0	1	5	2	3	0	0	20	0	**10**	5	**20**	0	5	5	**20**
	7	10	2	2	1	1	5	3	4	2	2	12	13	5	5	8	7	5	5	8
	Mean	11.5	1.3	1.3	1.3	1.6	5.3	2.7	3.6	2.0	1.4	11.6	12.6	5.1	5.1	8.1	7.1	4.9	5.1	8.3
Research	1	0	0	1	3	1	10	5	5	5	5	5	**40**	5	5	3	2	2	1	2
	2	15	3	3	3	6	12.5	5	2.5	2.5	2.5	1.5	15	1.5	1.5	9	1.5	3	7.5	4.5
	3	2	1	1	1	1	5	2	1	3	1	10	10	**10**	**10**	10	10	5	7	10
	4	21	1	1	1	1	2	4	1	2	1	4	12	5	5	4	10	7	6	12
	5	1	1	1	5	2	3	5	**10**	1	1	5	30	5	**10**	5	5	2	5	3
	Mean	7.8	1.2	1.4	2.6	2.2	6.5	4.2	3.9	2.7	2.1	5.1	21.4	5.3	6.3	6.2	5.7	3.8	5.3	6.3
ENGO	1	10	5	3	3	3	10	4	9	5	4	7	10	3	5	3	10	2	2	2
	2	18	5	4	4	5	7	2	3	5	5	10	3	3	3	3	7	3	5	5
	3	15	**10**	**10**	**10**	**10**	10	2	2	2	2	5	14	2	2	1	1	2	0	0
	4	12	8	4	4	12	4	4	6	4	2	3	9	6	6	3	3	4	3	3
	5	14	7	5	5	8	8	3	5	4	3	6	9	4	4	3	5	3	2	2
	Mean	13.8	7.0	5.2	5.2	7.6	7.8	3	5	4	3.2	6.2	9	3.6	4	2.6	5.2	2.8	2.4	2.4
Government	1	11	3	1	3	8	10	4	6	**8**	**6**	4	2	2	2	7	5	6	6	6
	2	2	1	1	1	2	**18**	2	**10**	4	1	2	8	2	2	2	**22**	2	1	18
	3	**39**	0	0	1	0	2	2	0	3	1	18	1	1	1	18	1	2	1	9
	4	15	8.75	8.75	8.75	8.75	2	3	2	2	1	5	5	5	5	5	5	3.5	3	3.5
	5	20	5	5	5	5	2	2	2	4	2	9	5	5	5	3	3	**8**	5	5
	6	20	5	5	5	5	6	**10**	2	5	2	10	8	1	3	2	1	5	2	3
	7	4	1	2	5	8	4	1.5	3	1	0.5	**25**	10	5	5	5	5	7	4	4
	Mean	15.9	3.4	3.3	4.1	5.3	6.3	3.5	3.6	3.9	1.9	10.4	5.6	3.0	3.3	6.0	6.0	4.8	3.1	6.9
	Overall mean	12.5	3.1	2.7	3.2	4.0	6.4	3.3	3.9	3.1	2.1	8.8	11.6	4.2	4.6	6.0	6.1	4.2	4.0	6.3

On average, and as expected, environmentally grouped experts rated environmental criteria highest, followed by economic, social then engineering criteria. The weights of the categorised criteria, compared by expert group, are presented in Figure 41 showing the criteria means, minimums, maximums and ranges. Research experts ranked economic criteria highest, followed by engineering, social then environmental criteria. Government experts rated environmental criteria highest, followed by economic, engineering then social criteria. Industry experts rated economic criteria highest, followed by engineering, environmental then social criteria. Overall, economic criteria were the highest weighted on average, followed by environmental, engineering and then social criteria. As CCS is a large-scale technology, and thus engenders high costs, a focus on economic considerations is expected.

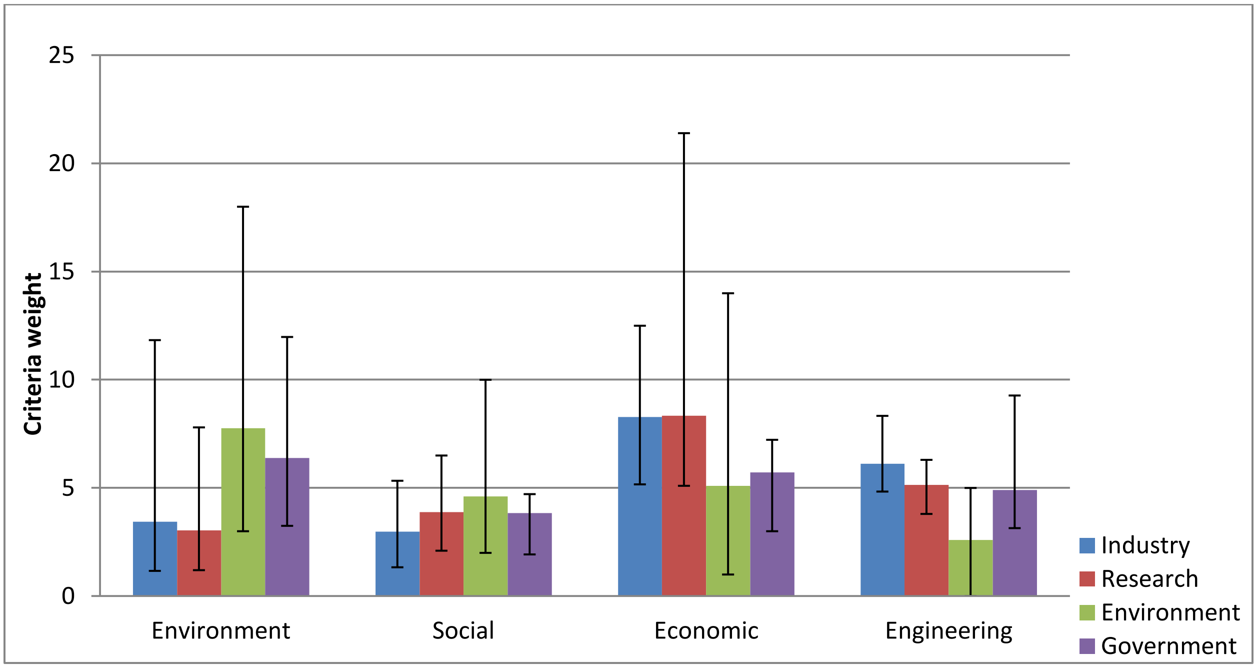

Figure 41 Group CCS expert criteria weight by category showing mean, minimum and maximum values

6.4.2 CCS Expert Self-Assessed Confidence

There were large variations in expert criteria confidence levels as almost all criteria had a minimum of one (lowest possible) and a maximum of four or five (see Figure 42). By interviewing experts with knowledge in each of the criteria areas, we were able to improve the reliability of our results as at least one expert (and usually many more) gave a confidence of four or five for every criterion. If criteria are included in an assessment in which the DMs have very poor knowledge, then the results would have a higher-level of uncertainty. Including experts who cumulatively have expertise in all criteria, even if not individually, limits this problem. Providing contextual information about all criteria, such as health or environmental regulatory limits, values for comparable projects and a strong understanding of the project proponent's assets and liabilities will also increase the level of confidence of DMs. The wide range in expert criteria confidence levels exposes the high level of uncertainty in experts' decisions for CCS. As CCS is a complex technology with broad risks and consequences, the DMs must include experts from at least the four major areas, environmental, social, economic, and engineering.

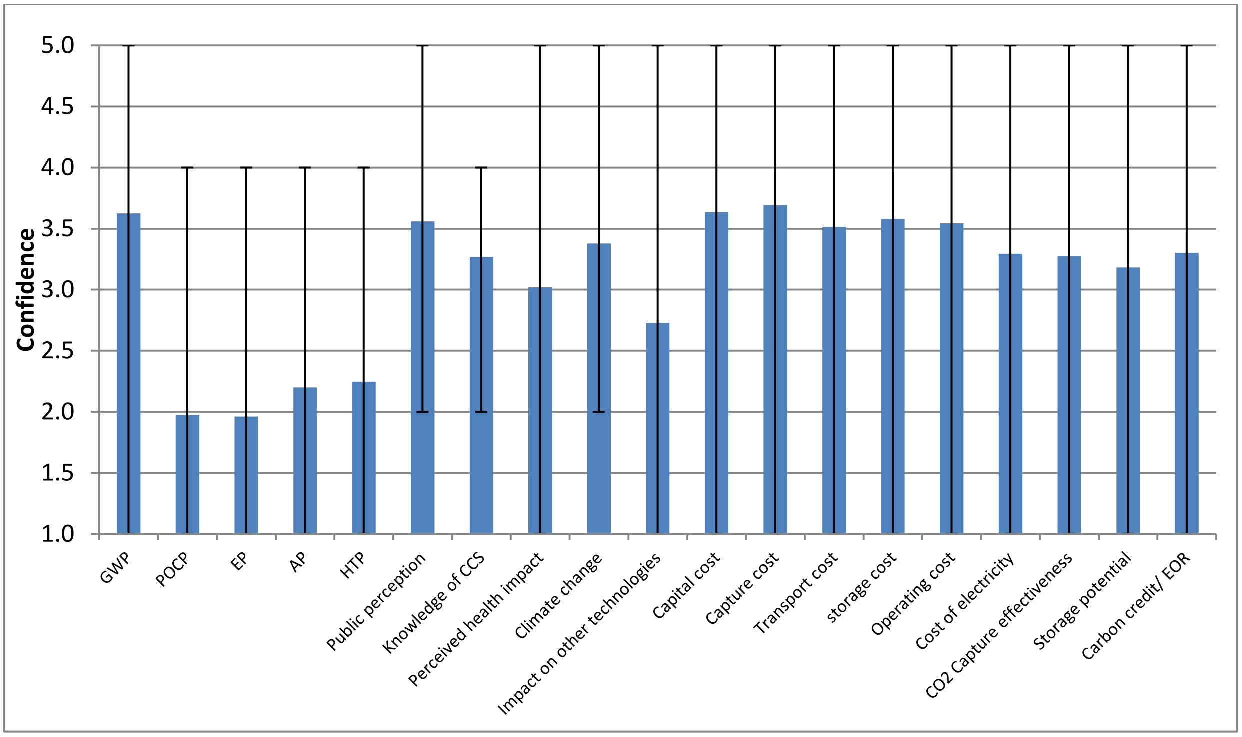

Figure 42 Criteria confidence levels for CCS experts using all participant responses showing the minimum, maximum and range

CCS industry experts were the most confident about economic criteria, followed by engineering, social and then environmental criteria categories (see Figure 43) suggesting a better understanding of economic issues in general. The research experts had the same pattern as industry experts, however they were less pronounced than industry experts in their confidence levels. Environmental experts expressed the most confidence in their weighting for social criteria followed by economic, environmental and then engineering criteria. Government experts were most confident about their social weights, followed by engineering, economic and then environmental criteria. The highest level of confidence over all four groups was for economic criteria with environmental criteria eliciting the least amount of confidence. Only the industry experts rated economic criteria with a mean confidence level of over 80%. The other criteria responses received only confidence levels between 34% and 76% indicating a low level of confidence overall. As there were no expert groups with high confidence levels for all criterion areas, including multiple DMs from each expert group will increase overall confidence and reduce uncertainty.

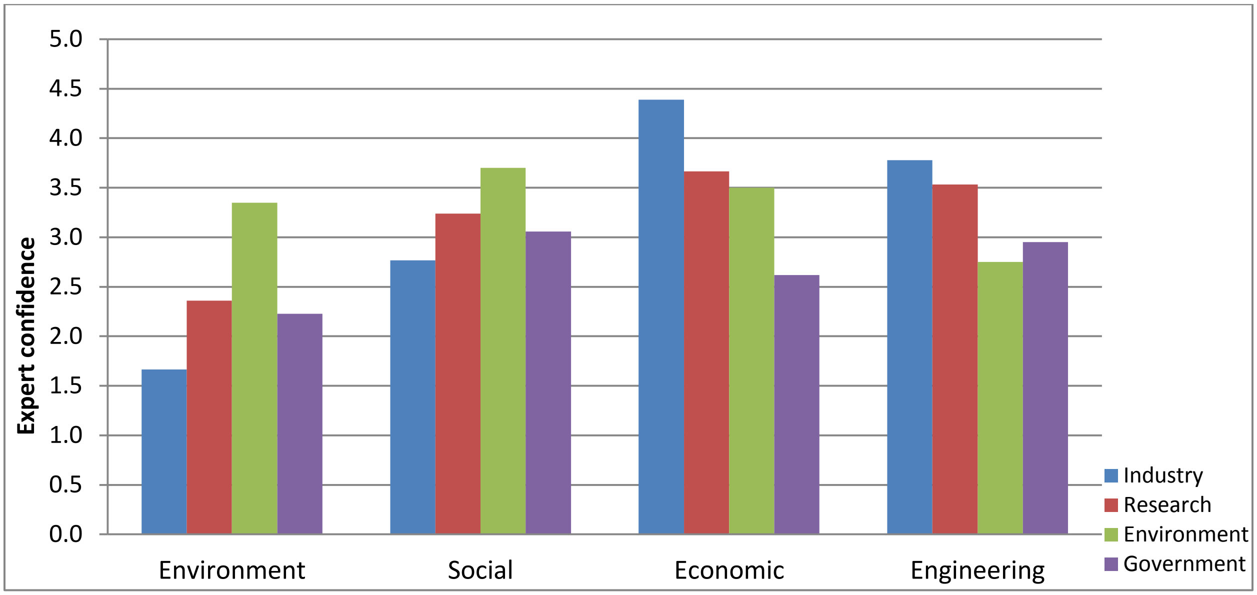

Figure 43 Expert confidence for criteria categories by CCS expert group

6.4.3 Model Simulation Results

The criteria weights for each CCS expert group were input to the model to determine how different DM viewpoints could impact the scoring and ranking of the projects. The experts' weights were used as a proxy to DMs from the different group backgrounds. The model was then run for 100,000 iterations using Monte Carlo simulation to simulate the possible outcomes of the criteria values to determine the projects' scores. The model was run four separate times using the mean criteria weights for each of the expert groups, followed by four runs using a sampling of each groups' weights (see Table 23). The model was then run again twice using a mean of all experts' weights and a sampling of their weights. Using only the criteria which had confidence values of three, four or five, the model was run twice more for a total of 12 runs. Using the mean scores for the projects, the projects were ranked, where a higher score is preferred. Multiple Monte Carlo simulations were run using different DM's weights to understand how changes in confidence and expertise influence the results. A graph showing the three projects' probability distribution for their scores is shown in Figure 44 using a sampling of criterion weights using all CCS experts' responses.

Table 23 CCS expert weight groups used to run the Monte Carlo simulations

Weight type used for each simulation	Expert groups means	Expert groups sampling	All experts mean	All experts sampling	All experts high confidence means	All experts high confidence sampling
Number of runs	4	4	1	1	1	1

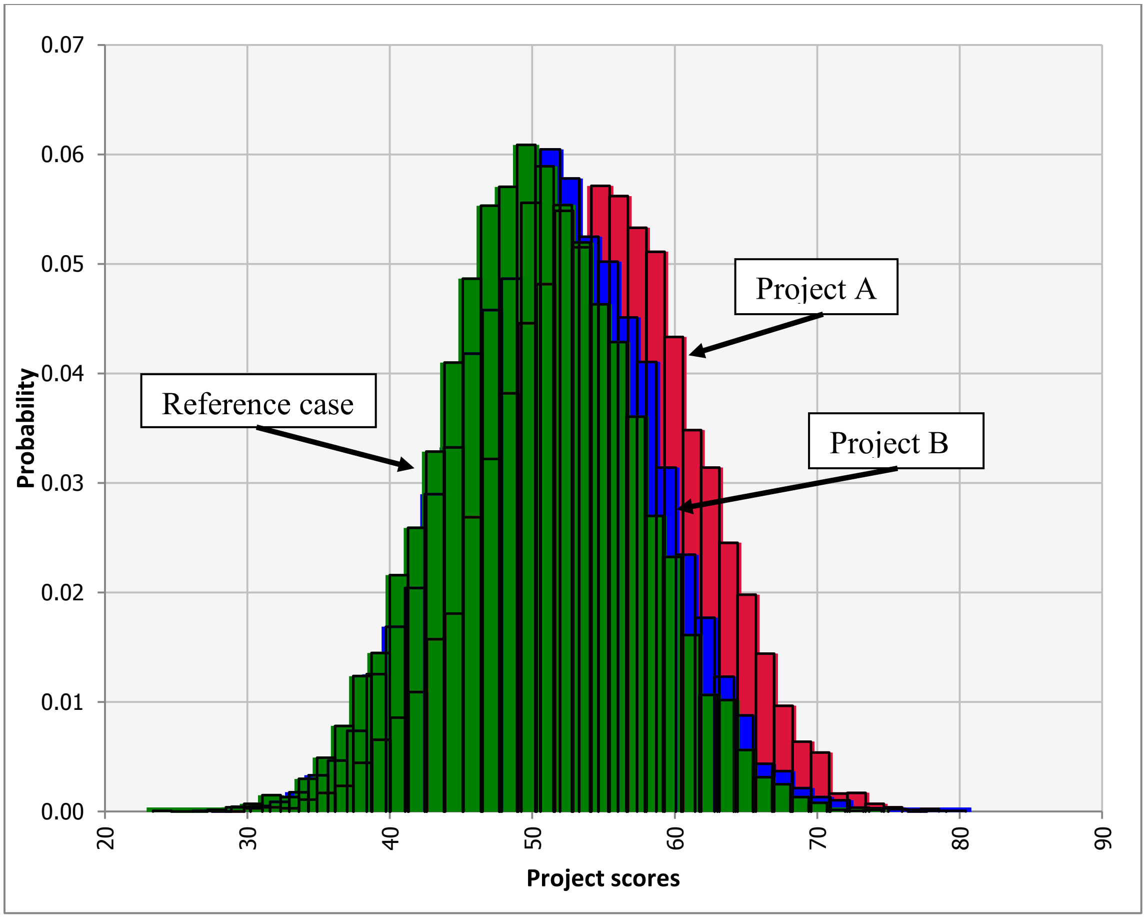

Figure 44 Probability distributions of the scores for Project A, B and Reference case using the aggregated criterion weights from all CCS experts

The results of the model simulation, including project rankings, using mean weights for each of environmental, research, government and industry groups are shown in Table 24. The authors found that despite the differences in CCS expertise and preferences for criteria weights, the experts tended to prefer Project A over Projects B or the Reference case based on an average project score. There were however, significant differences in how often (how many of the Monte Carlo simulations) resulted in the projects being the preferred choice as well as the ranking between projects B and the Reference case. Relying solely on the mean project score obscures these differences which may be important to DMs, especially if there is significant uncertainty in the criteria values. Using the full distribution of possible project scores DMs are able to tailor their decisions to avoid potentially low scores (even if the project has a high mean score).

Table 24 Average and distribution scores for the projects following the Monte Carlo simulation. The mean expected project score using weights from the four expert groups are shown followed by the project ranking for that group and % of iterations that the project was ranked as the preferred project. The lower section of the table displays the same information while using probabilistic sampling of the full distribution of expert criterion weights for the Monte Carlo simulation

Average weights	**Environmental mean score**	**Rank**	**% ranked 1**	**Research mean score**	**Rank**	**% ranked 1**	**Government mean score**	**Rank**	**% ranked 1**	**Industry mean score**	**Rank**	**% ranked 1**
Project A	48.38	1	34	53.74	1	35	54.23	1	47	62.12	1	35
Project B	46.88	2	33	50.19	3	32	52.87	2	37	56.97	3	32
Reference case	46.82	3	33	51.72	2	33	48.97	3	16	57.09	2	32

Distribution weights	**Environmental mean score**	**Rank**	**% ranked 1**	**Research mean score**	**Rank**	**% ranked 1**	**Government mean score**	**Rank**	**% ranked 1**	**Industry mean score**	**Rank**	**% ranked 1**
Project A	49.15	1	34	43.06	1	34	54.73	1	35	53.74	1	35
Project B	47.08	2	33	41.99	3	33	52.51	2	34	49.93	3	32
Reference case	46.85	3	33	42.48	2	33	48.78	3	31	50.88	2	33

Using both this sampling of all experts' weights as well as mean expert's weights for each criterion, the model was run again and results are shown in the lower half of Table 24. For all the CCS expert sampled weights, the values were normalized to ensure that each project was compared on an equal basis where the weights summed to 100 for each iteration of the simulation. Because each criterion was considered independently, the weights were sampled independently as well. Since there was variation in the CCS experts' weights, sampling of the weights meant that the total weights for each project in general would not sum to 100. A project that had higher weights in total than another project would therefore have an unfair advantage. The sampling was used to assess the relative difference in weights between criteria. Normalizing the weights kept the relative weights of the criteria the same within each project and enabled the projects to be compared on an equivalent basis.

The model was run again accounting for the confidence values for each expert's weights. The expert weights were not divided into expert groupings. Instead, those criteria that only had confidence levels of 2 or less were excluded for this analysis. When an expert was not confident about their weight on one criterion, it was excluded; however, the rest of their weightings remained. This left 65% of the expert weightings with confidences either of three, four or five. The weights were multiplied by the confidence value and then normalised. Criteria with high levels of confidence were emphasised by this process. Both a mean of all experts confidence weights, as well as a sampling of all weights, were used to run the model. The results are shown in Table 25.

Table 25 Average and distribution scores for the projects showing mean expected score and % of iterations ranked as the preferred project using weights for all CCS experts with confidence levels of three or more

	Distribution weights score	**Rank**	**% ranked 1**	**Average weights score**	**Rank**	**% ranked 1**	**Confident average score**	**Rank**	**% ranked 1**	**Confident distribution score**	**Rank**	**% ranked 1**
Project A	54.57	1	56	54.51	1	58	54.48	1	35	54.40	1	35
Project B	51.54	2	25	51.53	2	25	51.18	2	33	51.53	2	33
Reference Case	50.28	3	20	50.35	3	16	49.80	3	32	49.82	3	32

Project A was the preferred option for all variations of the analysis based on expected mean score. When only weights with confidences of three, four or five were used for the simulation, the three projects ranked almost identically with Project A only being ranked as the preferred option 35% of the time. There was no difference in project ranking when using a mean of expert criteria weights or a sampling of expert criteria weights. There was, however, a much wider distribution in project scores. As compared with an analysis that selected projects solely on the expected outcome of the projects mean score, this more in-depth analysis provided substantially different results. Since the projects were considered as very similar by the confident experts, a comprehensive assessment of the differences provided by the model will help DMs fully understand the tradeoffs between the projects.

6.4.4 One-Way Sensitivity Analysis

A one-way sensitivity analysis was conducted on the criteria to better understand how the uncertainty in criteria values impacted project ranking and thus selection. The impact on Project A's score when each criterion's mean value is varied by ±10% is displayed in Figure 45 with a Tornado diagram. Tornado diagrams for Project B and the Reference case showed similar results to Project A. For Project A, changes in the CO_2 capture efficiency criterion values have the largest impact on the project's score. Although CO_2 capture efficiency did not usually have a high weight assigned to it by the CCS experts, meaning that it was not considered very important to their decision, because it had a relatively narrow distribution of values, a 10% deviation from its mean represented a substantial change in its utility value and thus score. Therefore, under expected conditions, CO_2 capture efficiency was not a major contributor to project selection, however if the CO_2 capture efficiency was unexpectedly poor, it would have a strong bearing on the project selection. Understanding how much the criteria values can change is thus important towards understanding how robust the decisions are under many conditions. As the three projects had distributions of expected means that were usually within only a few points, a deviation of 10% in any of the criteria values would be sufficient to alter the rankings of the projects. The projects in this case study therefore are very sensitive to the criteria values which may not be the case if the criteria have large ranges in potential values.

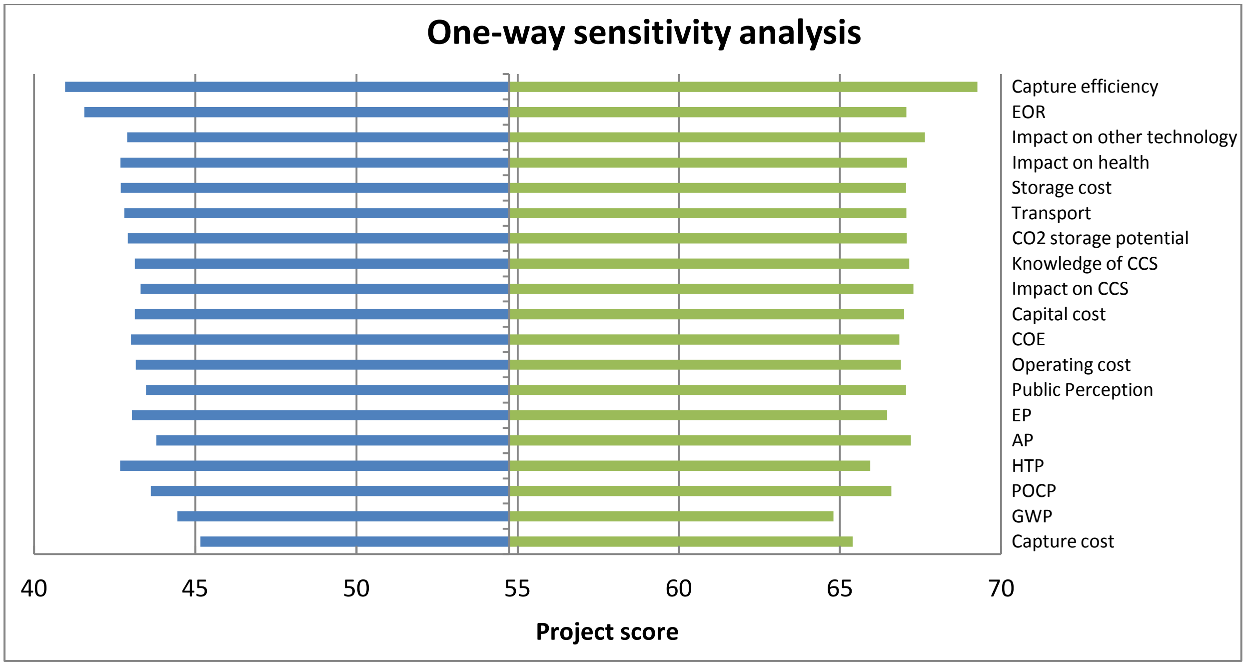

Figure 45 One-way sensitivity analysis of criteria on the overall score of Project A indicating that capture efficiency has the highest sensitivity while capture cost has the lowest sensitivity. As the diagram is predominantly uniform, instead of tapered in a tornado shape, the criteria all have similar impacts on the overall score of Project A.

6.4.5 Critical Event Analysis

The mitigation actions were also compared to determine which option would be preferred. We used a decision tree to compare the three projects with combinations of mitigation actions. Selecting the preferred mitigation action, like selecting the preferred project, is not necessarily a straightforward process. Mitigation selection can be impacted by DMs' risk profiles which are created during the utility elicitation process in Step 7. In the iteration of the simulation leading to the graph below, the optimal choice is to select Project A and both mitigation actions 1 and 2 as this yields the highest score (see shaded grey areas on Figure 46 to see the ideal selection path), which was also the option with the highest mean score over 100,000 thousand iterations. The highest possible score was to choose no mitigation action (since choosing a mitigation action has a small cost even if no critical event occurs). Choosing all three mitigation actions was the safest option, as it limited the most extreme impacts from the critical events. DMs would therefore need to make tradeoffs between choosing the options that provide the highest expected score, to avoid options with potentially severely negative outcomes, and ones which have the highest potential outcome but not necessarily the highest mean expected outcome. Each of the model steps comprehensively and transparently provide DMs with an added level of information to help DMs make the choice that best reflects their preferences.

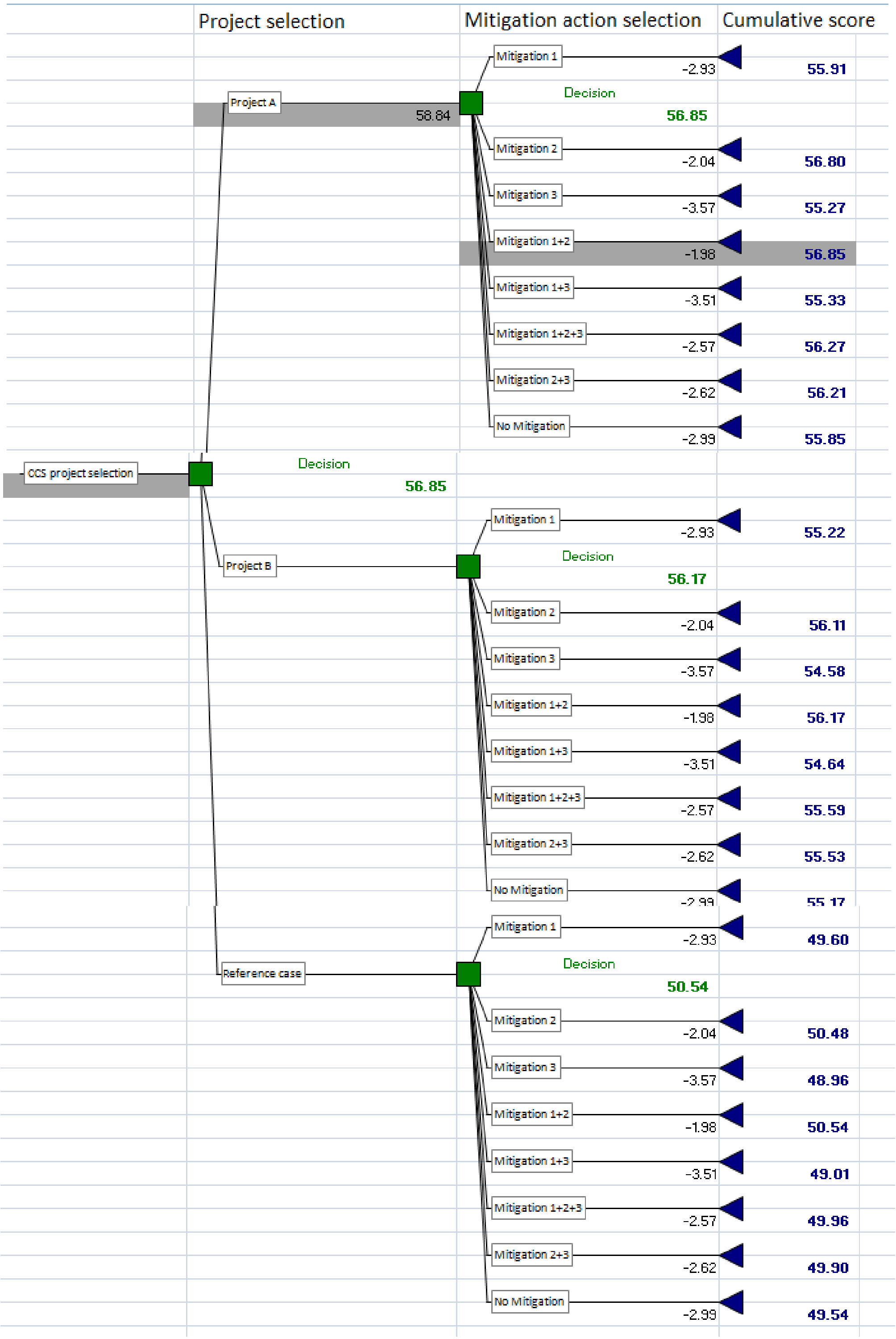

Figure 46 Critical event analysis using a decision tree with a sample outcome. The optimal decision path is outlined in shaded gray as it corresponds with the highest project score

6.5 DISCUSSION OF MODEL AND CCS EXPERT COMMENTS

Subsequent to providing expert criteria weights and confidences, many experts provided comments on the model. The comments were organised into three general recommendations: model methodology, criteria and data selection, and application of the model to different scenarios. These recommendations are outlined below with discussion.

6.5.1 Model Methodology

One common recommendation from experts for this model was that it should be used to assess project criteria in a stepwise manner. Criteria could be categorized into essential and non-essential groups, or by the different stages during the decision-making process where they should be assessed. Projects could then be filtered by values of criteria such as a minimum CO_2 storage size, maximum cost, or minimum CO_2 reduction, after which the projects that met the thresholds would be assessed by subsequent criteria until the projects are assessed in full. Their scores from each stage would still be summed to give an overall project score. This study did involve a stepwise assessment, however the survey portion focused on just one step of the analysis. To simplify the pilot study, each project was considered to have reached an acceptable value on each of the criteria chosen so that all criteria could be compared during one stage. It was also suggested by a few experts that the real decisions boil down to economic considerations and all the other criteria represent roadblocks, unless they reach a certain minimum threshold level, although the results indicate that environmental, social and engineering criteria are very important to the decision and cannot always be expressed in economic terms (Kelman, 1981 and Cavallaro, 2009). The model did also incorporate minimum and maximum thresholds, however, they were not explored in depth in the participant survey portion of the pilot study.

Utility curves were used to represent the non-linearity in preferences as values for criteria change. Through discussion with participants, it was found that most participants would prefer to develop preference curves representing their expert opinion of how each criterion can behave in reality and directly develop the curves using graphs so that they could visualize their choices. This was in contrast to choosing between lottery trade-offs, which the experts considered too abstract. Participants could also express their opinion of the suitability of criteria which would occasionally have discontinuities where the usefulness of a criterion's value was constant until a specific point after which it would increase dramatically and then potentially flatten, creating a stair-like pattern (see Figure 47). Such utility preferences could not be converted into traditional utility curves and had to be expressed as conditional equations or look-up databases for the Monte Carlo simulations. This is an area of research focus for the authors in order to provide this functionality to the model.

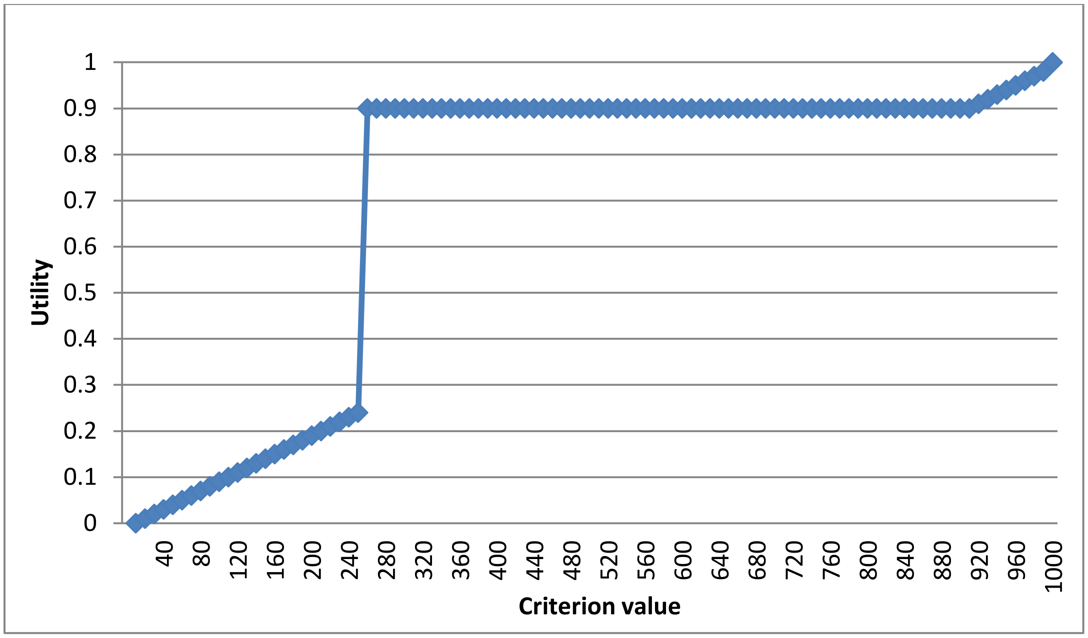

Figure 47 Sample utility curve showing discontinuities in utility as the criterion value increases

6.5.2 Criteria and Data Selection

The experts that participated in this survey were from many varied fields involving CCS. Their comments on the model and which criteria should be included reflected this variation. This range in experts led to many further suggested criteria to be included in the model for future studies that fit their individual needs (see Table 26 for other CCS criteria that the model can accommodate). The criteria areas receiving the most comments were related to CO_2 storage conditions, groundwater impacts (perceived and real) and economic indicators such as measuring total costs in terms of CO_2 avoided, and whether to include carbon credits or carbon taxes. As the model is developed as a framework, DMs are able to include the criteria that best reflect their needs for each decision analysis.

Table 26 Criteria recommended for future applications of the model

Criteria	Number of times suggested
Impact on groundwater quality	4
Cost per tonne of CO_2 avoided	3
Number of well penetrations in area	3
CO_2 carbon credits (carbon market/carbon tax)	3
Reservoir integrity	3
Long term permanence of CO_2	2
Perceived impact on land values	2
Reservoir injectivity capacity/ injection rate	2
Long term liability (local regulatory conditions)	2
Age or status of existing wells	2
GHG removal (or reduction)	1
Annual CO_2 emission reductions	1
Total CO_2 emission reduction potential	1
Local attitudes to specific proposed project	1
Reservoir pressure	1
Monitoring potential	1
Local seismicity	1
Local faults	1
Hydrogeology conditions	1
Storage depth	1
Temperature	1
Porosity	1
Permeability	1
Caprock thickness	1
Volume of groundwater removed	1
Existing usable infrastructure	1
Diagenesis conditions	1
Natural gas prices (external competing projects)	1
Public perception of specific project	1
Public perception of company developing project	1
Reputational CCS experience of developer	1
Land footprint from facility	1
Potential impacts from surface development	1
Perceived impact on potable groundwater	1
Impact on flora	1
Impact on fauna	1
Impact on endangered animals	1
Length of time required for permitting	1
Original oil in place (OOIP) (Important for EOR)	1
Government funding/ subsidies	1

There were also criteria that experts believed could be excluded from similar CCS analyses. The economic criteria chosen for this study are interrelated and could be condensed into one indicator such as \$/tonne of CO_2 avoided. As this study was exploratory, we were interested in how CCS experts would weigh the economic criteria and whether the weights would be proportional to the relative costs of the economic criteria. This was the reason that economic criteria were separated into project cost components instead of using one aggregate indicator such as net present value. We found that experts did not weigh the economic criteria proportional to their relative costs. This may indicate that dividing criteria into their constituent parts (e.g. dividing total project cost into capture, transportation, storage, and operating costs, among others) will help DMs to better assess projects. Providing an even more detailed assessment may be beneficial to DMs since it may reveal opportunities for improvement and outline when the costs (or impacts) may occur, potentially resulting in different project preferences.

Because the current model application is high-level, many of the criteria are interrelated and each criterion depends on several more-detailed criteria. CO_2 storage volume for instance could be characterized by porosity, permeability, specific gravity, reservoir depth, and confining layer thickness, among many other factors. When assessing projects, it can be difficult to properly assess options using multi-dimensional and complex criteria such as CO_2 storage. There is a trade-off between including many detailed criteria which can become overwhelming in their complexity and quantity, and using few high-level criteria that are manageable but may reduce the clarity and confidence of DMs' judgements. One way to address this problem is through hierarchical criteria weighting. DMs could weigh detailed criteria which are combined into higher-level criteria, which in turn are compared with other high-level criteria (see Figure 48 for a CCS example). DMs would therefore weight criteria on two or more levels. This would require more time but could be beneficial when assessing large complex projects.

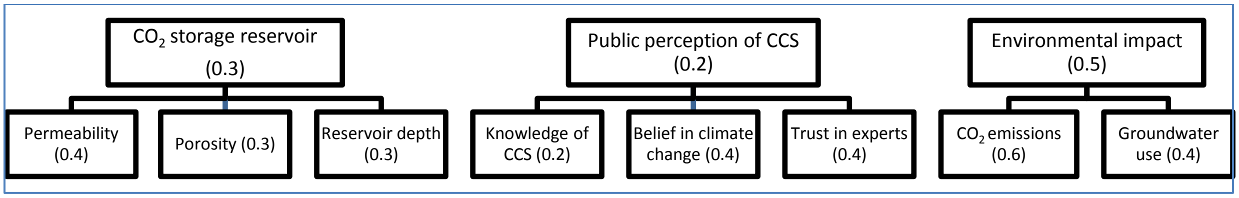

Figure 48 Sample hierarchical criteria weighting for a simplified CCS project

Other critiques of the model include the requirement for extensive and good quality data, which is hard to obtain. As the model explicitly incorporates data and DM uncertainty through sensitivity analysis and critical event analysis, and is meant to help inform DMs rather than be prescriptive, this should be less of a concern than models which use a 'black box' approach. Although not explicitly stated by the CCS experts during the survey, many of the environmental and social criteria were considered unnecessary as they were given very low weights, and occasionally values of zero. Since these same criteria often had very low confidence values it is unknown whether these weightings were due to unfamiliarity with those criteria or a true belief in their unimportance. Whether there is a lack of familiarity with criteria will be important to determine with future CCS assessments in the early stages of decision analysis in order to avoid uncertain weightings by including experts in that area. Furthermore, experts suggested presenting the data in more common terms (e.g. social data using a scale between 0 and 100 instead of 0-1 and excluding decimal points) so that the differences between criteria are more easily compared.

6.5.3 Application of the Model to Different Scenarios

As the model is able to assess a broad set of diverse projects, using a wide variety of criteria, and it is also very adaptable, it was well received by CCS experts who believed that it could be adapted to fit many CCS decision problems. The most commonly suggested uses of the model were for benchmarking projects either for governmental funding competitions or within large energy companies. In both cases, it was suggested that the model should focus either on higher-level aspects of CCS decisions or on more detailed components of CCS rather than the combination used here. For high-level assessments, the model could be used to eliminate inferior projects using a screening approach in which only a few critical criteria are assessed initially followed by a more in-depth analysis of the 'top' projects. Within an organization, the model could be used to assess environmental and social criteria alongside net present value for project selection. For more detailed studies it was suggested that decisions about issues such as CO_2 storage location could be assessed using criteria based on detailed, high-quality data, in which case more focus would be given to the interplay and interdependence of the criteria.

The results shown in the graphs and tables are based upon a small sample size and may be masking detailed patterns, due to the use of criterion means which can be easily skewed by a few expert opinion outliers. Environmental criteria for instance had both very highly weighted criteria as well as very low weighted criteria. If some criteria had not been included, the mean weights may have been significantly different. This was also reflected in the wide-ranging level of confidence between the criteria by the experts.

The model currently only assesses a few critical events for the project. This is in part due to extremely limited data and the need for project-specific conditions and experts for many criteria's data to be useful. For example, there have been no recorded large-scale anthropogenic CO_2 leaks (the most significant critical event). Indeed, many of the possible negative events have not been thoroughly researched and the information that does exist lies with experts, thus thorough critical event analysis is difficult. Nevertheless, the number and type of critical events that could be assessed using this model is only limited by the imagination and needs of the DMs.

The critical events chosen for this initial assessment and used in the survey demonstration represent negative events. The mitigation strategies chosen are actions mostly focused on remediating an event or detecting a leak prior to significant surface leakage in the negative event of a CO_2 leak occurring. This is in contrast to a possible focus on preventative measures, a suggestion made by participants. The model could be expanded to include detailed assessments using bow-tie risk assessments of possible hazards. Participants also suggested that positive critical events could be assessed in future studies, including events such as the development of a carbon market, government subsidies, competing technologies becoming unfavorable (e.g. nuclear energy) and more certain government regulations. In addition, critical event analysis does not necessarily need to be assessing 'events' as such and can be used to represent external factors such fuel costs, costs of borrowing or other factors that could impact a project. Uncertainties in external factors (such as fuel prices) could be correlated with criteria data to supplement the uncertainty distributions of the criteria.

The case study chosen is not necessarily a realistic example of how a CCS project would be chosen by energy companies and the model can be modified to address various scenarios. Governments could make decisions for the energy company such as in a competition for funding which requires many criteria and stakeholders and needs to be transparent. When developing a project, however, energy companies are usually only responsible for one part of the CCS development chain. Projects often include partnerships between a combination of utilities (power plant operators), pipeline operators, oil and gas companies (for well injection and EOR operations), financial supporters, CO_2 suppliers, researchers and reservoir owners. Each group may have different priorities (and risk attitudes) and thus would use the model in different ways (Rai *et al.,* 2009). However, the model can accommodate this set of multiple stakeholders. The model could be used in a detailed assessment of storage options, CO_2 capture technology choices, or transportation method, among other choices made by all or a select number of the above mentioned groups. A higher-level assessment could be conducted afterward using the detailed studies as input data so that the overall project could be compared with competing similar projects.

6.6 CONCLUSION

Depending on which expert groups' weights were used to run the model, the ranking of the projects differed. Project A was consistently the preferred choice, based on its mean expected project score. The percentage of time that it was the preferred choice, however, did change substantially between the simulations using different group's criteria weights.

The pilot study validated the risk model both in terms of demonstrating its functionality and its benefits over other decision models, as well as receiving positive responses from CCS experts. The main strength of this model lies with its flexibility, enabling it to assess a wide range of projects and criteria and its ability to be adapted to any comparative assessment problem. The pilot study also demonstrates the many aspects of the model and how they could be applied to CCS and other large-scale energy decisions. For instance, only portions of the model need to be used if only mitigation actions are being compared. The results of this pilot study provide insights into how groups of CCS experts differ in their consideration of CCS risks and values of projects. It also shows how different CCS stakeholders have different preferences, which can substantially impact the project selection. The results of the survey should not necessarily be taken as representative of the population at large in part due to the low sample size, hypothetical case study, and geographical differences between participants preferences. Nevertheless, the transparency of the model allows a DM to see the breadth of factors that influence a decision (criteria, preferences, uncertainty, and impact of different stakeholders). This aspect of the model could be particularly attractive to governments for funding competitions in which different groups' priorities need to be taken into account. The transparency of the model can also provide insights into the trade-offs between the relative merits of projects with different strengths and weaknesses.

Future work could focus on other applications of the model, such as assessing more detailed decision problems such as deciding between alternate CO_2 storage locations. The model could also be adapted to address higher-level decision problems where CCS is compared with other climate change mitigation actions. All studies would benefit significantly from more accurate data and more expert opinion. Working with a specific CCS project would allow for the model elements to be more thoroughly tested. As more data is collected, a database of expert opinion, criteria values, criteria weights and utility curves could be developed. Where data is lacking, DMs could use this database as a proxy for real world data and to estimate how different groups may react to a project.

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CHAPTER 7
CONCLUSION

The following summary statements are designed to complement the narrower conclusions embedded in the Chapters that were structured in publication format (4, 5 and 6).

Climate change is a dynamic problem that requires a wide range of actions to mitigate. Decision analyses are becoming more complex and taking into account environmental and social factors into what were traditionally on economic and engineering factors. CCS is a complex and multi-faceted climate change mitigation technology with wide ranging impacts. CCS development has many risks and uncertainties that could benefit from more thorough decision analyses. These uncertainties include large costs, public perception, ownership and liability, reliability and scale of CO_2 storage and the integration of CCS into broader climate mitigation strategies.

A small but rapidly growing field of CCS research is being conducted to address these issues. A literature review of recent CCS assessment methods exposed a lack of interdisciplinary research. Studies tended to focus on one assessment method and incorporate criteria from within either environmental, social, economic or engineering fields in isolation from other factors. An interdisciplinary list of criteria that were most often included in these separate CCS assessment studies was proposed for use in holistically assessing future high level CCS decisions. There are advantages to interdisciplinary research as some problems represent more than the sum of their parts. Through discussions with experts, CCS was found to be such a case due to its scale, large uncertainties and wide impacts. Interdisciplinary research can complement detailed, single-discipline studies to provide holistic assessments of decisions. Detailed studies can feed into broader interdisciplinary studies by providing high quality data for DMs to interpret and make broader conclusions. A balance is needed between detailed studies and very high-level studies however in order to avoid over-simplifying decisions by ignoring the interactions between detailed aspects of CCS.

There are decision analysis models that use risk to assess CCS decisions as well as models that use MCDA methods. There are however few that do both and explicitly address uncertainty and risk. A risk assessment model using a MCDA approach was developed to assess CCS decisions which incorporate social, economic, engineering and environmental criteria. The model integrates many analysis elements including utility curves, criteria weighting, uncertainty, decision trees, thresholds, Monte Carlo simulation and sensitivity analysis in a novel way to address CCS-specific decisions.

This transparent risk model easily displays distributions of possible project scores and sensitivity analysis to aid DMs in comprehensively assessing the options that best reflects their preferences (see Figures 47 and 48). The visual nature of the assessment outcomes, alongside statistical information, provides clarity to the DM. By involving the DM in the major assessment steps and using a transparent approach, the model avoids the pitfalls of ‘black box’ models where DMs distrust the results due to a lack of understanding the model process. DMs are able to easily modify their inputs, vary the criteria values and perform sensitivity analyses with the model.

‘What if’ scenarios are included in critical event analysis where extreme events specific to CCS are considered with respect to their impact on the projects’ scores. Possible mitigation methods are assessed for their effectiveness at reducing the probability and severity of critical events. The model aims to be transparent, reflect individual DM’s preferences and to give a greater understanding of complex decisions. The model aims to be informative rather than prescriptive in that there is no one right answer. Allowing for a high degree of model flexibility and the ability to test decisions enables a more interactive relationship between the DM and the risk model which results in a better understanding of the robustness of the model results and the DM’s decisions.

Using data collected from the literature review as well as FEED studies, expert opinion and project-specific information, a database of criterion values was created. From the database, probability distributions were created for the criteria representing their expected values. A case study was conducted to demonstrate the benefits of the model and apply it to a realistic scenario. CCS experts from research, government, industry and ENGO groups in Alberta were provided with a scenario where they are acting as senior DMs who must choose between three realistic CCS projects. They then reviewed a summary sheet outlining the projects, criteria and the decision model. Experts provided their preferences (in the form of criteria weights) for their opinion of the relative importance of the criteria for selecting between CCS projects. Experts were also asked for their confidences for each criterion weighting. The case study projects were assessed using the model under several scenarios using Monte Carlos simulation. The projects were first assessed using a distribution of CCS experts’ weights from each group. The assessment was conducted again using only expert’s criteria weights that had high confidence levels. Project A had the highest mean score in all cases however the ranking of Project B and Reference case depended on which groups' weights were used. The project scores were also compared using sensitivity analysis and critical event analysis. The case study demonstrated the benefits of using this more complex risk model rather than relying on expected outcomes by showing that there are many other factors to consider when selecting complex CCS projects. The assessment revealed that small variations in expert's criteria weights and criteria values could change the ranking of the projects. By modeling DM's preferences and including criterion value thresholds, an individualized assessment is created that explores the nuances of multi-faceted problems that cannot be understood with models that use expected outcomes as a measure of project success and lack the capacity to take uncertainty into account.

Although the responses were very positive from CCS experts, there were comments on how to improve the model to meet specific CCS decision needs. The CCS experts came from a wide range of backgrounds and as such their comments and suggestions reflected the areas with which they were most familiar. Industry experts tended to place more emphasis in their weights on economic factors, while government and environmental groups on average wanted more emphasis placed on environmental and social considerations. Research groups had comments that were in between those of industry, government and environmental groups. Although the experts were from different CCS fields, economic criteria were the highest weighted overall, indicating that CCS costs still dominate decisions despite project cancelations due to public opposition and environmental concerns (Anderson et al., 2012). Experts also suggested including specific criteria that they use in their work such as groundwater pollution, land use and water removal. A list of factors was created with the highest weighted criteria that the DMs considered to be the major CCS risk factors. These are criteria that have the largest impact on CCS decisions and could benefit from further research to improve the implementation of CCS.

There are several limitations to the case study conducted in Alberta and the CCS risk model in general. The case study involved interviews with 40 CCS experts and elicited responses from 24 of these experts. This was due in part to requiring participants be experts in at least one aspect of CCS, the small field of CCS experts and the time requirements for the experts to participate in the study. The small number of participants limits the applicability and broader implications of the results specific to the case study. The model has face validity based on simulation runs and expert feedback, however CCS is still a new technology and therefore there is no long term historical basis with which to evaluate the effectiveness of this model on real world CCS decisions.

Future work could focus on implementing the model in real world situations where CCS is being considered for development or projects are vying for government funding. There has been interest in using the model to address both more high-level questions such as how CCS broadly fits into climate change mitigation strategies such as energy conservation, solar and wind power generation, or on more detailed assessments that look at a particular question such as selecting a capture technology or CO_2 storage site. Because the model is more of a methodology or framework rather than a specific assessment tool, there do not need to be fundamental changes to the model structure in order to adapt it to different applications. With appropriate data and expert opinion, the model is able to address any comprehensive decision.

The model currently is not very user friendly as it requires four different software programs to operate the Monte Carlo simulations and to provide the statistical information about the projects. If the model continues to demonstrate utility, it may be beneficial to develop the model into a more complete package with instructions and tutorials. This is currently being explored. As more primary data and expert opinions are collected, a database could be developed where users could select typical criteria and data with which to simulate the model with. For example, a DM could select a range of environmental opinions from the database as a proxy for local environmental groups if real world data is unavailable to see how their projects may be received.

A further use for the model that was frequently suggested by CCS experts is for benchmarking projects. Regulatory agencies or large energy companies could evaluate projects that they currently approve. Using the same model, they could assess future projects by how they compare with the benchmarked projects. The model would give a holistic assessment of the strengths and weaknesses of the new project relative to previously approved projects. A company or regulatory agency could use agreed-upon utility curves and criteria weights. As conditions change either internally or through external forces, the curves and criteria weights could be updated. This could be an iterative process where projects are periodically assessed to ensure that they are still viable. Widely different projects could still be compared as long as the list of criteria is sufficiently comprehensive to accommodate the relevant criteria for all projects. If a criterion does not apply to a certain project, then it would simply receive a score of zero. Since the criteria are only compared relatively to each other, the overall scores of the projects will still reflect the viability of projects relative to each other.

The risk model has demonstrated that a more comprehensive, versatile method could be beneficial for assessing CCS decisions. As CCS is an expensive large-scale technology and climate change is considered as a major global concern, proper decision analysis models are needed to ensure that DMs are provided with comprehensive, transparent and adaptable tools with which to make their decisions.

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Appendix 1A Climate Change

This appendix elaborates on the general overview provided in Chapter 2 to provide more details on the concepts described therein. The information provided below gives more context to the decision analysis presented in the thesis.

1A.1 GREENHOUSE GASES

CO_2 is the main contributor to anthropogenic climate change despite its low GWP, due to its very high total emissions. The global carbon cycle is presented in Figure 49. The global warming potentials of CO_2 and other GHGs are shown in Table 27 for comparison. Each of the major GHGs is described in turn.

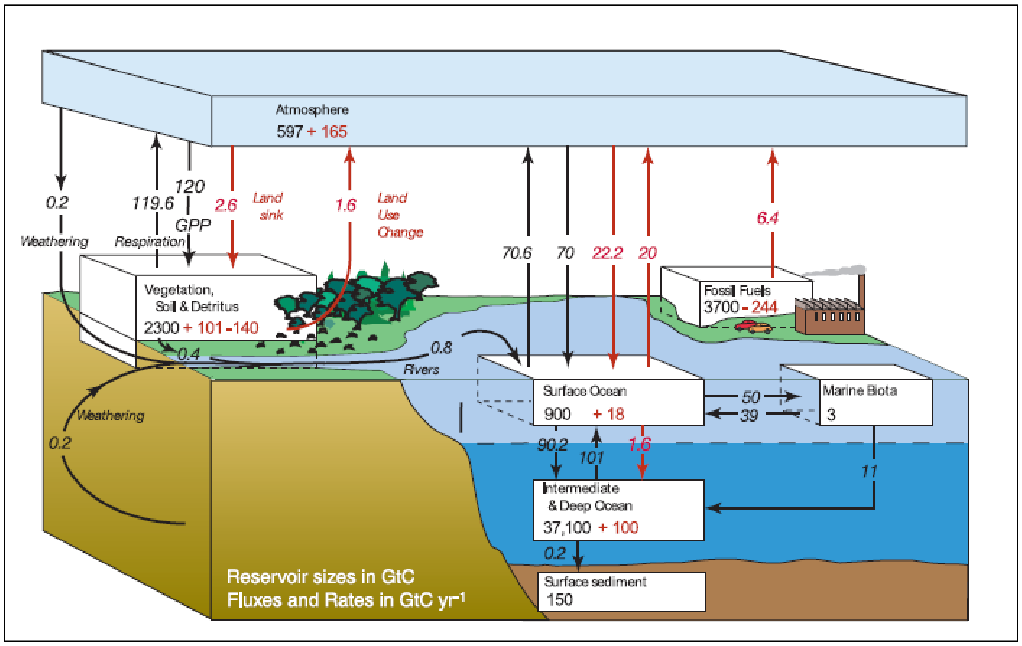

Figure 49 Global carbon cycle for the the years 1990 to 2000. The main annual fluxes in Gt of Carbon (GtC) per year show the natural fluxes of carbon in black with the anthropogenic fluxes in red. (IPCC, 2007)

Table 27 Global warming potentials (UNFCCC, nda)

Species	**Chemical formula**	**Lifetime (years)**[12]	**Global warming potential (time horizon)**		
			20 years	**100 years**	**500 years**
Carbon Dioxide	CO_2	Variable (5-200)[13]	1	1	1
Methane	CH_4	12±3	56	21	6.5
Nitrous Oxide	N_2O	120	280	310	170
Sulphur Hexafluoride	SF_6	3200	16,300	23,900	34,900

Methane has the second highest radiative forcing (RF) of the long-lived greenhouse gases, after CO_2. Atmospheric concentrations of CH_4 have fluctuated between 400ppb and 700ppb over the past 650,000 years. The concentrations of CH_4 in 2005 were approximately 1,774ppb based on a

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[12] Lifetime refers to the length of time that a species remains in the atmosphere and contributes to global warming (UNFCCC, nda)

[13] Inman, 2008

worldwide average indicating a large increase in concentrations over natural variations (IPCC, 2007). Atmospheric concentrations of CH_4 are quite low compared with CO_2, however due to the much higher GWP of CH_4 estimates (ranging between 6.5 and 51 times that of CO_2) its contribution to climate change is still significant. Although not fully understood, the increase in atmospheric CH_4 has been slowing over the past decade. The sources of CH_4 that contribute to atmospheric concentrations include wetlands, rice agriculture, biomass burning and ruminant animals (IPCC, 2007). CH_4 eventually reacts in the atmosphere with OH to produce CH_3 and water which falls to the ground where it is stored for long periods of time.

N_2O has the fourth highest radiative forcing after CO_2, CH_4 and CFC-12. Pre-industrial levels of N_2O were in the range of 270ppb and are now approximately 319ppb (IPCC, 2007). Over the past few decades, concentrations of N_2O have risen steadily by approximately 0.25%/yr. The atmospheric lifetime of N_2O is 114 years and also impacts Ozone depletion. Major sources are not well known, but are thought to be from coastal waters and from soils due to human induced land-use changes (IPCC, 2007).

HCFCs are a series of anthropogenic chemicals used in refrigeration, foam, and fire fighting solvents to replace chlorofluorocarbons (CFCs) which contributed significantly to the atmospheric ozone hole (UNEP, 2007). HCFCs vary considerably in composition and characteristics, and have atmospheric lifetimes that range from 1.4 to 270 years. Their concentrations show a continuous increase over time. HCFCs are to be phased out between 2013 and 2040 as new products replace them (UNEP, 2007). HCFCs are very effective infrared absorbers; however their concentrations are very small, thus contributing approximately 2% to the total radiative forcing of anthropogenic gases.

Similar to HCFCs, PFCs were introduced as a replacement to traditional ozone depleting refrigerants. PFCs are estimated to contribute only 0.2% of the radiative forcing from greenhouse gases (IPCC/TEAP, 2005), however their atmospheric lifetimes range between 1,000 and 50,000 years. A variety of organic solvents have been developed to replace PFCs which have much lower GWPs (IPCC/TEAP, 2005).

Sulphur hexafluoride is predominantly anthropogenic in origin and is used in small quantities in the electricity sector for insulating switchgears and circuit breakers and in die casting (Olivier and Bakker, 2002). SF_6 has an atmospheric lifetime of approximately 3,200 years (Environment Canada, 2010). SF_6 has a very high GWP (23,900 at 100 years) but due to low concentrations has a relatively small impact on climate change.

The major source of CO_2 from fossil fuels comes from the oxidation of carbon when fuels are combusted. In biomass production, the fermentation process releases CO_2 when the sugar is converted to alcohol. Typically when drilling for natural gas, there is naturally-occurring CO_2 associated with the gas which must be removed prior to transport in pipelines. In the past this extra CO_2 was simply vented to the atmosphere, but is sometimes collected to be used in enhanced oil recovery (EOR) projects.

In cement production, the source of CO_2 emissions is from calcinations, which is the thermal decomposition of limestone and dolomite (IPCC, 2005). Cement production involves heating calcium carbonate ($CaCO_3$) along with small amounts of aluminum, iron and silicon to produce slaked lime. This causes a chemical process called calcination to occur. Coal, oil or natural gas is used to provide the high temperatures necessary for this process. Worldwide, there are approximately 1,200 point sources large enough to be effective with post-combustion CCS process. The cement production process produces CO_2 concentrations of between 14 and 33% and works most effectively with post-combustion capture (Rackley, 2010).

Appendix 1B Details on the Use and Application of CCS

1B.1 CAPTURE TECHNOLOGIES

1B.1.1 Pre-Combustion CO_2 Capture

Pre-combustion CO_2 capture technologies have been in use in some form for many years, mostly in fertilizer manufacturing and hydrogen production (IPCC, 2005). The process of capturing CO_2 prior to combustion is currently more complex and expensive than post-combustion CO_2 capture.

The pre-combustion process involves partially oxidizing fossil fuels which then react with steam to form CO_2 and H_2. Hydrogen is then used directly as a fuel combustion source. The flue gas concentrations of CO_2 in pre-combustion capture are much higher than those in post-combustion capture and are typically in the range of 15-60% (Rackley, 2010). The different separation technologies for pre-combustion capture are shown in Table 28.

Table 28 Current separation technologies and future technologies under development for pre-combustion CO_2 capture (Rackley, 2010)

Technology	**Currently developed technologies**	**Example technologies under development**
Absorption-based separation	• Physical solvents such as Selexol, Fluor processes, and chemical solvents	• Novel solvents to improve performance; improved design of processes and equipment
Adsorption-based separation		• Zeolite, activated carbon, carbonates, hydrotalcites and silicates
Membrane separation		• Metal membrane water-gas-shift (WGS) reactors; ion transport membranes
Cryogenic separation	• CO_2 liquefaction	• Hybrid cryogenic plus membrane processes

1B.1.2 Oxyfuel CO_2 Capture

Oxyfuel capture is a less mature technology than either post- or pre-combustion capture and involves injecting a high purity oxygen stream into the fossil fuel combustion phase of CCS. The major costs for oxyfuel CO_2 capture arise from separating oxygen from air, but again, like pre-combustion, this process results in a very pure CO_2 gas stream (almost 100%), lowering costs in the separation phase.

The flue gas concentrations from a fossil-fuelled power plant can greatly impact the costs, and methods used for CO_2 capture. The impurities also need to be removed by separate processes which incurs additional costs. The typical fossil-fuelled flue gas concentrations for coal and natural gas-fired power plants are shown in Table 19.

Table 29 Typical fossil-fuelled flue gas concentrations and parameters (Adapted from Rackley, 2010)

Parameter	**Typical ranges of values**
Pressure	Approximately atmospheric pressure
Temperature	30-80°C
CO_2	• Coal-fired,14% • Natural gas-fired, 4%
O_2	• Coal-fired, 5% • Natural gas-fired, 15%
N_2	Approximately 81%
SO_x	• Coal-fired, 500-5,000ppm • Natural gas-fired, less than 1ppm
NO_x	• Coal-fired, 100-1,000ppm • Natural gas-fired, 100-500ppm
Particulates	• Coal-fired, 1,000-10,000mg/m^3 • Natural gas-fired, 10mg/m^3

1B.2 STORAGE TYPES

There are many potential storage reservoirs for CO_2. CO2 most efficiently fits into pore spaces at a depth of 2km or more (see Figure 50). Below is a description of the most promising storage types as well as the mechanisms for preventing the release of CO_2 out of the reservoirs

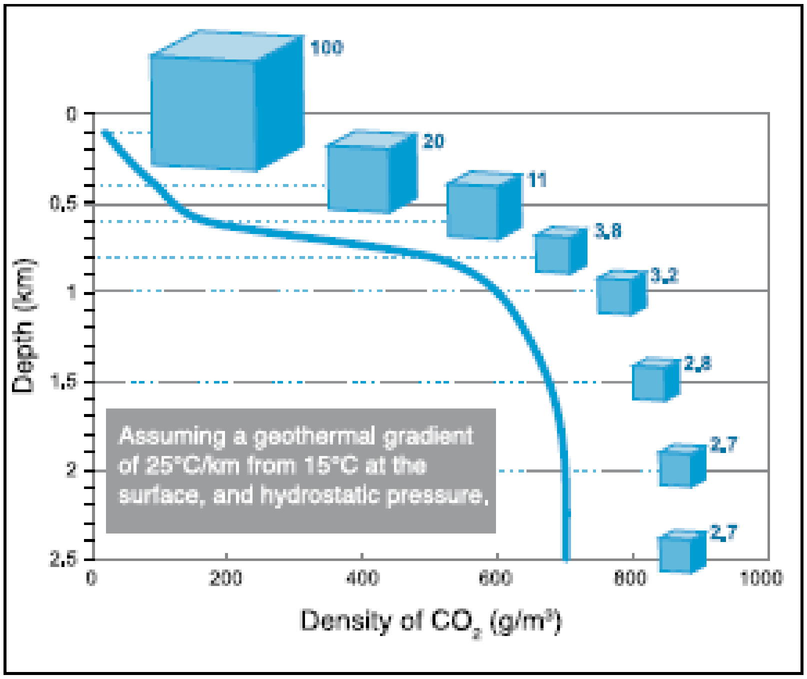

Figure 50 Density of CO_2 as a function of depth underground. After approximately 2km, the density of CO_2 does not significantly decrease (IPCC, 2005)

1B.2.1 Oil and Gas Reservoirs

Depleted oil and gas reservoirs are natural sites for storing CO_2 because they once contained oil and gas (usually with small quantities of CO_2) for millions of years. Research suggests that they could continue to store CO_2 for the foreseeable future as long as all wells are properly sealed and there is not a significant geological disturbance creating a transportation path to the surface. The estimated worldwide storage capacity of such reservoirs is 675–900 $GtCO_2$ (IPCC, 2005).

Because CO_2 is significantly less viscous than water and oil, it has a high mobility which results in it bypassing many pore spaces. Average saturation is thus only between 30 and 60% (IPCC, 2005). This mobility is important in enhanced oil recovery (EOR) as not all the oil is displaced and then released. In oil formations, there is a slight buoyancy effect driving CO_2 upwards. In natural gas formations however the opposite is true as CO_2 is denser and migrates downwards, helping to further secure the CO_2 (IPCC, 2005). Detailed studies will need to be conducted to determine how the CO_2 will react in these reservoirs. Although oil and gas have been stored underground for millions of years, the introduction of a CO_2 and any injection fluids will change the reservoir characteristics. Injection pressures will have to be carefully monitored to ensure that fractures are not created or reopened.

1B.2.2 Deep Saline Formations

Deep saline aquifers do not provide any direct economic benefit from CO_2 injection unlike oil and gas reservoirs, however they are much more common and are estimated to have storage capacities roughly twice as large (Rackley, 2010). These aquifers have high salt concentrations and are not suitable for human or agricultural use. They may however be of some use in geothermal energy, so care must be taken to identify potential competing uses before development as CO_2 sinks. These aquifers are far less studied than oil and gas reservoirs and thus CO_2 storage capacity estimates range from anywhere between 1,000-10,000 $GtCO_2$ worldwide (IPCC, 2005).

CO_2 in saline formations is between 30 and 50% less dense than the formation fluid, resulting in strong upward buoyancy. This upward buoyancy means that there must be a caprock above the formation to ensure that the CO_2 is contained. This creates a cavity below where CO_2 can be safely stored. The Sleipner project in the North Sea is the most well-studied example of saline formation CO_2 storage (Rackley, 2010).

1B.2.3 Unmineable Coal-Beds

Coal-beds that are too difficult to mine are another potential storage site for CO_2. Estimates of CO_2 storage in these coal-beds range from 3–200Gt (IPCC, 2005). Potential sites are located in sedimentary basins and are expected to be near many of the world's emission sources. This option is in the demonstration stage and may eventually lead to enhancing methane production from such coal-beds.

As CO_2 flows from an injection well into coal formations, adsorption and desorption occurs. Swelling of the coal occurs and methane is then released, possibly for recapture and use as a fuel source (IPCC, 2005). Coal often adsorbs methane, but it has a higher affinity for CO_2, so when CO_2 is present, the coal will release methane (and other gases) and trap CO_2. This process is called enhanced coal-bed methane (ECBM). Injecting CO_2 can increase the recovery of methane, from 50% to upwards of 90% (Stevens *et al.,* 1996). Because increased pressure and stress reduce the permeability of coal (and thus there would be less methane adsorbed onto coal at increasing depth), most ECBM projects are within 1,000m of the surface. Although CO_2 is expected to be stored permanently on the coal-beds, long-term studies have not been conducted and there is a possibility that a disturbance or introduction of other fluids could cause their release (IPCC, 2005).

1B.2.4 Ocean Storage

CO_2 is negatively buoyant in seawater at approximately 3,000 meters below the ocean surface and deeper. This negative buoyancy means that CO_2 could be stored as a lake of supercritical fluid in depressions on the ocean floor without returning to the surface (Rackley, 2010). Natural pools have been observed near hydrothermal vents. These sites would be reached either by pipeline from shore or from platforms (IPCC, 2005). However, there is strong opposition from the public and environmental organizations against using oceans as a direct storage mechanism as CO_2 increases the acidity of ocean water and can cause calcium shells to dissolve (Rackley, 2010).

Injecting CO_2 into geological storage below the ocean floor is another option that would be less of a direct threat to humans as the distance is further from human habitation. The most suitable ocean sites would be near-shore on the continental shelves as the abyssal plain has sediments that are too thin and impermeable (IPCC, 2005). The cost of piping CO_2 increases substantially with distance underwater. Limited research has been conducted on storage in caverns, basalt and organic-rich shale.

1B.2.5 Trapping Below an Impermeable Confining Layer

The physical blockage of CO_2 is one of the most effective trapping mechanisms. The most common physical mechanisms for trapping CO_2 are shown in Figure 51. The most appropriate sites are those that have both an impermeable layer above and on the sides of the injection site as CO_2 will naturally migrate upwards due to its buoyancy. These layers should be thick and impermeable, or have very low permeability, without fractures and faults (IPCC, 2005). These layers are most commonly formed from shale and salt beds. Salt plumes are effective barriers since, over thousands to millions of years, salt slowly migrates upwards, thus deforming the surrounding stratigraphy and creating an effective cap on both the sides and above the injected CO_2. It is important to ensure that pressures are kept low enough that faults are not created or retriggered resulting in migration pathways for CO_2 (IPCC, 2005).

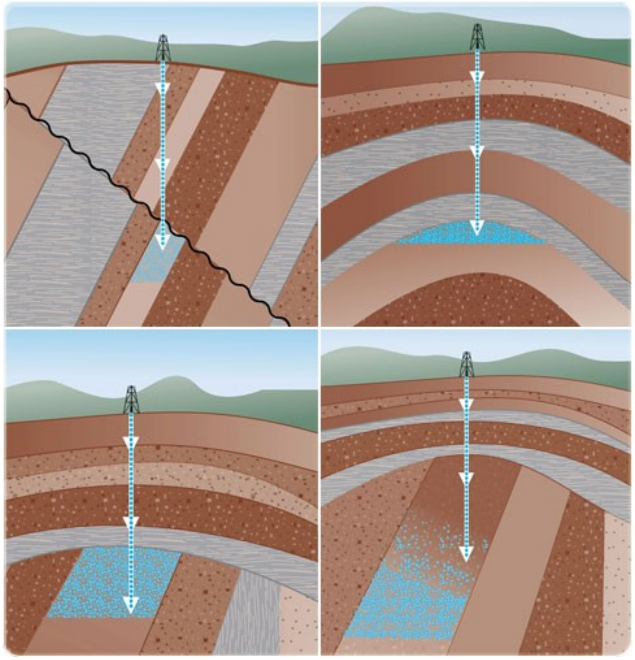

Figure 51 Schematic of physical trapping under an impermeable cap rock. Clockwise from the top left: fault trapping, anticline trapping, facies change trapping, and unconformity trapping (CO2CRC, 2010a)

1B.2.6 Retention as an Immobile Phase Trapped in Pore Spaces

As CO_2 travels through pore spaces along with formation fluids, a portion of the gas is retained by capillary forces in the pore spaces (see Figure 52). This occurs as the concentration of CO_2 falls below certain threshold levels. Over time this CO_2 will dissolve into the formation fluids. This is also referred to as residual CO_2 trapping and can immobilize significant quantities of CO_2. Residual trapping may trap between 15 and 25% of CO_2 in typical storage formations (IPCC, 2005).

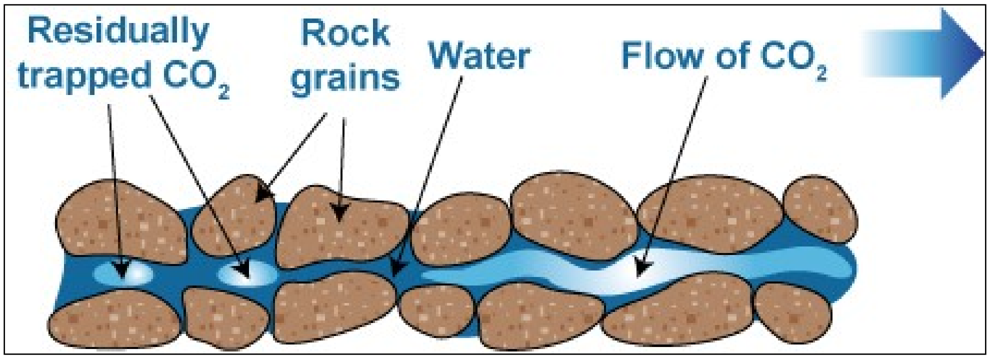

Figure 52 Capillary pressure traps CO_2 in rock pore spaces as CO_2 migrates through formation fluids (CO2CRC, 2010a)

1B.2.7 Dissolution into Formation Fluids

CO_2 dissolution occurs over many years so is not well understood in natural field conditions. Numerical simulations show that up to 30% of slow-moving CO_2 will dissolve into formation fluids within several decades. Over hundreds of years, CO_2 is expected to dissolve completely into formation fluids (IPCC, 2005). Once in a formation fluid, CO_2 is much less likely to escape and be released to the surface as it becomes less buoyant. CO_2 will however flow with the fluids which, depending on the situation, could result in eventual release to the surface in artesian wells, or remain in aquifers for thousands or even millions of years. These leakage pathways highlight the importance of choosing the proper locations and reservoir conditions for storing CO_2. In deep sedimentary basins the typical migration rates of formation fluids ranges from millimetres to centimetres per year (IPCC, 2005). These rates are far slower than if CO_2 were in a separate phase before dissolving. Dissolution is dependent on pressure, temperature and salinity, with CO_2 dissolving into a concentration between 20 and 60kg per $1m^2$ (IPCC, 2005).

1B.2.8 Reaction with Minerals to Produce Carbonate Minerals

Mineral trapping is both the slowest of the trapping mechanisms (taking up to thousands of years) and also the most secure. Mineral trapping can occur due to the following reaction (or variations): 3K-Feldspar + $2H_2O$ + $2CO_2$ ↔ Muscovite + 6Quartz + $2K^+$ +$2HCO_3^-$ (IPCC, 2005) where the CO_2 reacts to form a solid carbonate mineral. The processes that occur depend strongly on the formation minerals, the acidity and pressures. Some mineralization will occur within days of CO_2 being injected, while some reactions will take thousands of years. In the Weyburn-Midale project in Canada, it is expected that within 5,000 years, all the CO_2 will be either dissolved into the formation fluid or be converted to carbonate minerals effectively preventing the release of the gas to the atmosphere (Perkins *et al.,* 2005).

1B.3 STATE OF CCS WORLDWIDE

There are three large-scale CCS projects worldwide. These include Sleipner, Weyburn-Midale, and In Salah. Along with these large-scale projects, there is significant research into developing CCS in other situations as well as how CCS can fit into broader climate change mitigation strategies

1B.3.1 Sleipner

The Sleipner project, located approximately 250km offshore of Norway in the North Sea is the first large-scale CCS project, opening in 1996 (see Figure 53) (IPCC, 2005). The original project involved collecting oil from the Sleipner West Gas Field. The producing reservoir has approximately 9% CO_2 mixed in with the natural gas. A carbon tax in Norway made it less expensive to re-inject the CO_2 into geological storage rather than venting it into the atmosphere and paying the tax. The project injects CO_2 into a saline formation approximately 800m below the ocean floor near the natural gas reservoir. The program is operated by Statoil and the IEA Greenhouse Gas R&D Programme which monitors and oversees the injection of approximately 1 Mt CO_2 into the saline formation each year (IPCC, 2005). A total of 20 Mt CO_2 is expected to be injected over the lifetime of the project. Time-lapse seismic surveys and other reservoir studies show that the CO_2 plume extends over an area of more than $5km^2$. The caprock is an effective seal and models predict that the CO_2 will eventually dissolve into the formation water and sink, minimizing the risk of leakage (Lindeberg and Bergmo, 2003).

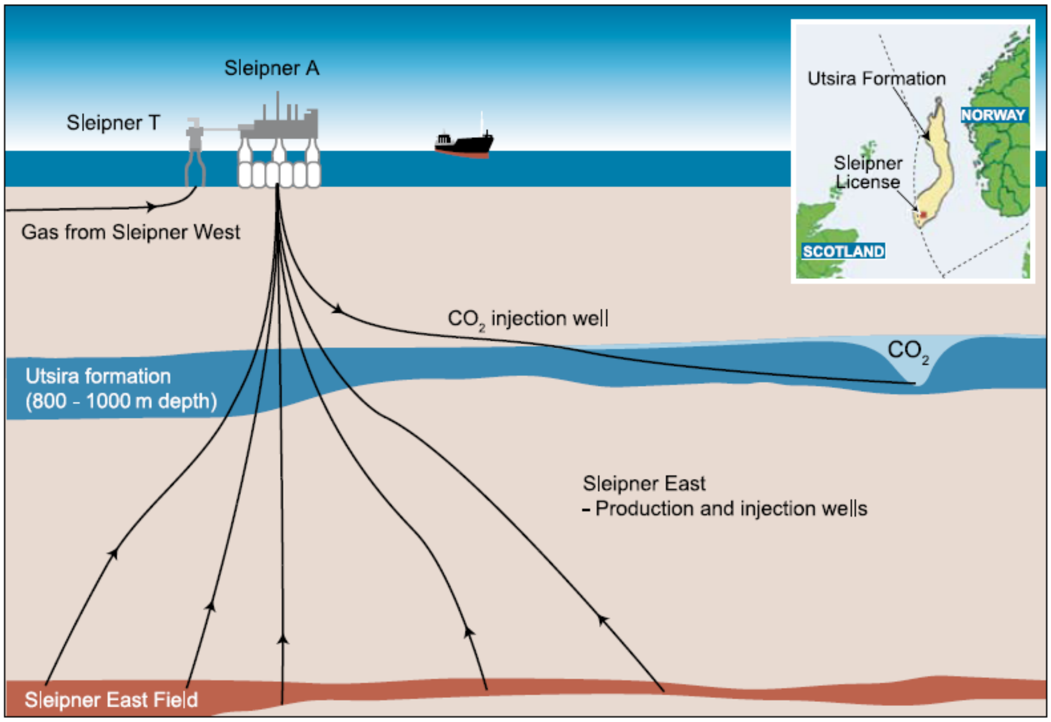

Figure 53 Simplified diagram of the Sleipner gas production and CO_2 storage project (IPCC, 2005)

1B.3.2 Weyburn-Midale

The Weyburn-Midale CO_2-EOR Project is located in southeastern Saskatchewan, Canada (see Figure 54). The project began in 2000 and involves dehydrating and compressing a highly pure CO_2 gas stream from a synthetic gas project located 325km south in Beulah, North Dakota. The CO_2 is a waste product of the process of converting natural gas into pure methane. The project injects between 3,000 and 5,000t/day of CO_2 into an old oil field for enhanced oil recovery (Moberg *et al.,* 2003). As oil is produced at Weyburn, CO_2 also comes up the wells. This CO_2 is then recompressed and injected back into the reservoir. The project is expected to store 20 $MtCO_2$ over its 20-25 year lifespan (White, 2005). In early 2011 a local homeowner claimed that a CO_2 leak from the Weyburn-Midale project was damaging the environment and killing flora and fauna. After an extensive investigation it was found that the CO_2 was naturally occurring and there was no leak from the CCS project (IPAC-CO_2, 2012).

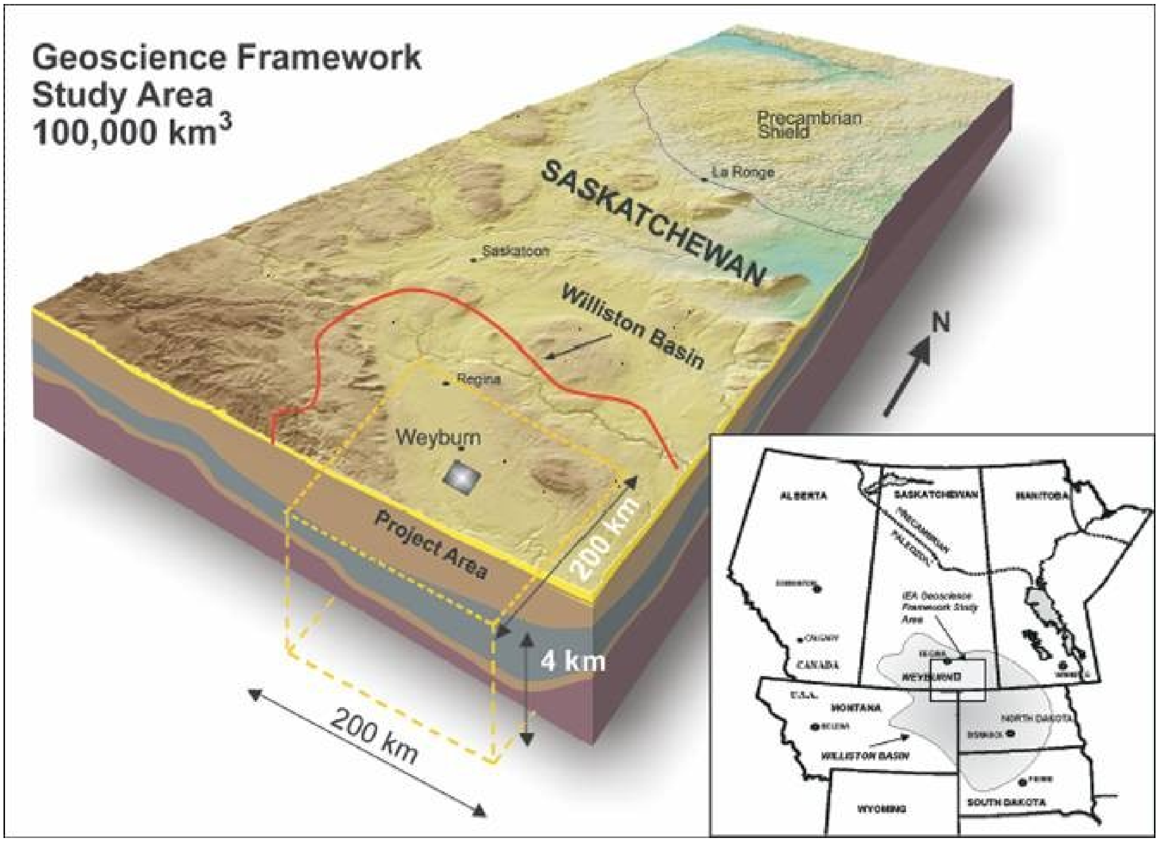

Figure 54 Weyburn-Midale CCS-EOR study area (PTRC, 2012)

1B.3.3 In Salah

The third commercial scale CCS plant is located in the central Saharan region of Algeria. The project involves producing natural gas which contains 10% CO_2 and stripping the CO_2 for reinjection before transporting the natural gas to Europe (IPCC, 2005). CO_2 injection began in 2004 with an estimated total storage of approximately 17 $MtCO_2$. The CO_2 is injected using three wells into a sandstone reservoir containing mostly water at a depth of approximately 1,800m (see Figure 55). Extensive monitoring at In Salah involves noble gas tracers, pressure surveys, tomography, gravity baseline studies, microbiological studies, seismic and geochemical surveys, which is starting to provide a very detailed view of the processes occurring in the sandstone formation (IPCC, 2005 and In Salah Gas, 2010).

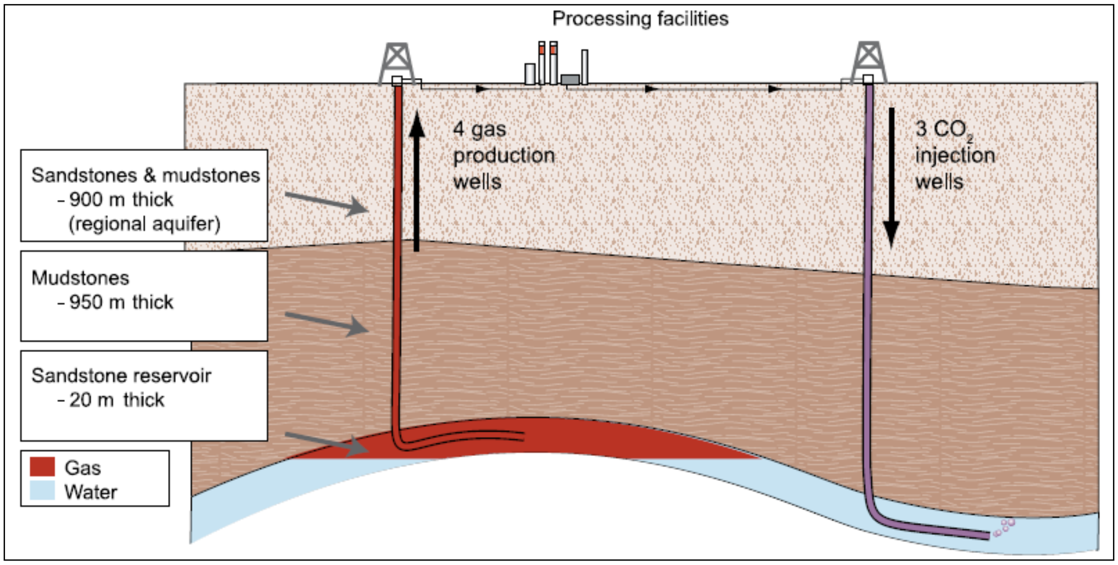

Figure 55 Schematic of the In Salah CCS gas project in Algeria (IPCC, 2005)

1B.3.4 Oil Reserves and Infrastructure

Worldwide there is an estimated 4,000 to 6,000 gigatonnes of oil and gas in geological reservoirs, representing the accumulation of hundreds of millions of years of biological and geological processes (Rackley, 2010). Although only a small fraction of these reserves can be extracted economically, there are still enough reserves to meet our energy demands for the foreseeable future, especially with the introduction of more efficient technologies, unconventional sources, energy conservation and renewable energy in niche markets.

There is a large embedded infrastructure in the developed world involving billions of dollars of power plants, power lines and distribution systems. This is also termed 'technological lock-in' whereby once we have decided on a type of technology, it becomes difficult and expensive to change, even if the alternative is less expensive; the costs of changing can be prohibitive (Meadowcroft and Langhelle, 2010). Weaning our energy economy off of fossil fuels will be a slow process. Minimal changes to the current energy infrastructure make CCS a useful option for the short term until more sustainable (non-fossil fuel based) options become feasible.

1B.3.5 Stabilization Wedges

It is predicted that there will be large increases in global energy demand this century, mostly in primary energy requirements from developing regions in Asia and Latin America. The energy demand in 2004 is expected to result in CO_2 emissions of approximately 7 billion tons per year by 2050 (see Figure 56 part A) (Pacala and Socolow, 2004). The IPCC believes that no single technology will provide the reductions in greenhouse gas emissions needed to achieve a stabilization of atmospheric concentrations (IPCC, 2005). Most scenarios predict that fossil fuels will be the major source of energy until at least the mid-21st century.

Developing climate stabilization wedges is a useful method for determining what global GHG emissions atmospheric concentrations could be with the introduction of mitigation actions to curb emissions. This method was proposed by Pacala and Socolow in 2004 where they showed that using existing technologies, our energy needs could be met while limiting our greenhouse gases to less than double pre-industrial levels (see Figure 56 part B) (Pacala and Socolow, 2004). Pacala and Socolow argue that these mitigation actions can, with investment and development, work in concert to significantly reduce GHGs. These stabilization scenarios all show that CCS will need to play an integral part of the solution with estimates of its possible share ranging from 15%-28% between 2009 and 2050, with estimates increasing to 55% of climate mitigation actions by 2100 (Dixon, 2009).

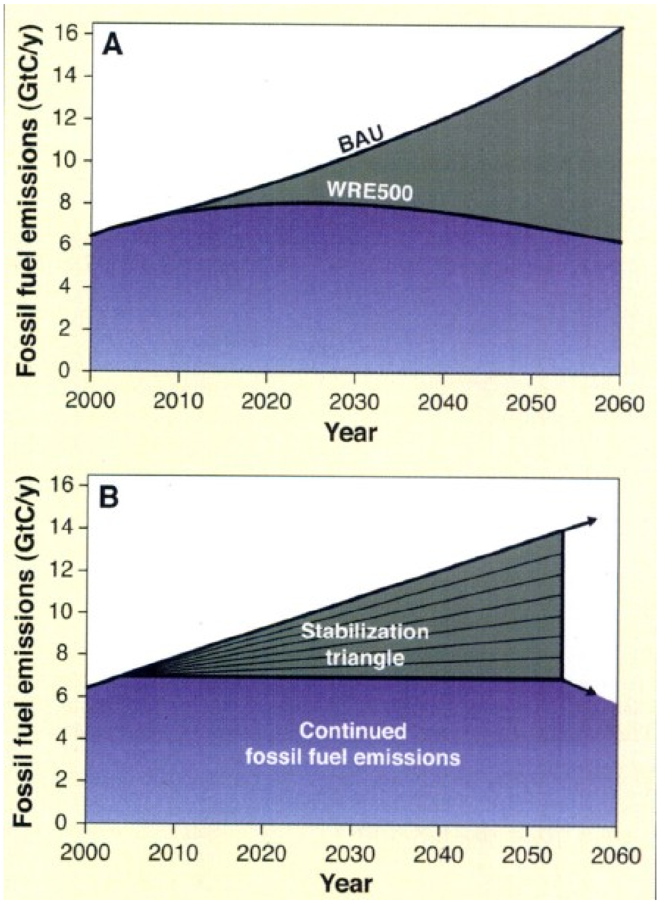

Figure 56 Projected emission scenarios based on Business as Usual (BAU). A and stabilization wedges as proposed by Wigley, Richels, and Edmonds (WRE), B (Wigley *et al.,* 1996; Pacala and Socolow, 2004)

There are many research groups worldwide conducting research on CCS and the number continues to increase. Most of the work is being conducted in either the capture or the storage portion of CCS. The methods and risks of transporting CCS are well known and is not a major roadblock to implementing CCS. The capture costs of CCS however are very high and will need to be reduced in order for CCS to be widely implemented (Riahi *et al.,* 2003). The other major area of research concerns the geological storing of CO_2. The mechanics of storing CO_2 are fairly well known, but the extent of storage volume worldwide is not well mapped, and there is uncertainty regarding the risk of leakage that needs to be better understood.

As CCS is a relatively new technology, economies of scale and learning from early projects are expected to substantially reduce costs and risks over time (IPCC, 2005). If the rate of technological learning for CCS follows the same path as that of sulphur removal technology, then the efficiency of CCS (and thus cost reductions) will improve by a factor of 4 between 2000 and 2100 (Riahi *et al.,* 2003; Rubin *et al.,* 2004b). The costs of capture are also expected to decline by between 20 and 30% over the period 2005–2015 (IPCC, 2005) although estimates vary widely (Lohwasser and Madlener, 2012) and actual costs are hard to determine since few commercial scale CCS projects have been developed. All the stabilization wedge models assume certain rates of learning which significantly affect the proportion that each technology contributes to climate mitigation.

1B.4 CANADIAN AND INTERNATIONAL PERSPECTIVES

CCS had been considered in the 1970s but did not gain any significant attention until the mid-1980s as a realistic climate mitigation action when concern regarding anthropogenic climate change increased and the technology matured (Meadowcroft and Langhelle, 2010). In the 1990s the International Energy Agency (IEA) developed a Greenhouse Gas Research and Development Programme to study climate mitigation actions. In 1992 the first major international CCS conference was hosted by the IEA. Significant funding provided and research conducted by governments and fossil fuel producers led to the first large-scale project at Sleipner in Norway (Meadowcroft and Langhelle, 2010). Research institutions and governments however still remained cautious, with the IPCC not even including the technology in its 1995 report on mitigation actions. The technology remained on the periphery with very limited public exposure and collaboration. It was not until 2005 that the IPCC recognized the potential of CCS as a climate mitigation action with its special report on CCS after several conferences and the recommendation of the UNFCCC. This was the first time that CCS had reached the greater public conscious (Meadowcroft and Langhelle, 2010).

Environmental problems such as acid rain, mercury emissions and other pollutants have historically been addressed by treating flue gases with chemicals to remove the pollutants. CCS works on similar principles and would on first glance be expected to be the main choice for climate mitigation actions. Part of the reason that CCS was initially avoided as a climate mitigation action in lieu of other options, such as energy switching and conservation, may be due to two reasons: firstly, many people believed that fossil fuels were the main cause of anthropogenic climate change and thus the solution must lie elsewhere; secondly, many of the industries and countries that were most connected to fossil fuels spent their time denying that climate change was a problem instead of promoting costly technological solutions (Meadowcroft and Langhelle, 2010). These detractors are now some of the biggest proponents and funders of CCS as they see it as a way for their industry to continue without large volumes of CO_2 emissions.

Since the publication of the IPCC Special Report on CCS in 2005 there has been an increasing push towards research and the construction of demonstration plants. This increased research has paralleled the increasing evidence for climate change. More international groups have been established, including the Carbon Sequestration Leadership Forum (CSLF), the International

Performance Assessment Centre for Geological Storage of CO_2 (IPAC-CO2), the Global CCS Institute (GCCSI), and more demonstration projects started such as the Weyburn-Midale project and In Salah project both discussed above. The European Union (EU) has also adopted a draft directive on CCS in 2008 to help steer its climate mitigation actions and international negotiations (Meadowcroft and Langhelle, 2010).

Non-governmental organisations (NGO)s can have a strong impact on public perception and by proxy, government action on environmental issues. The three largest NGO stakeholders that influence CCS advancement are the fossil fuel industry, the environmental community and the scientific community.

The fossil fuel industry has been one of the largest obstacles to mandating and achieving climate change action. As the science behind climate change strengthened and public opinion moved towards being in favour of action, the fossil fuel industry slowly changed as well. This change occurred first in European countries but was eventually followed by multinational companies based in the U.S. (Levy and Newell, 2000). As CCS provides a way to limit the impact on climate change while continuing to use fossil fuels, the fossil fuel industry saw the technology as a way to move forward in collaboration with the environmental and scientific community (Levy and Newell, 2000). It allowed for a compromise while still protecting their interests. Countries like Australia that have large indigenous coal reserves have followed a similar path to that of the fossil fuel industry in that it had initially attacked climate change science. Now, Australia sees CCS not only as a way to use its coal with low CO_2 emissions, but also as a way to secure its exports of coal and natural gas to those who have mandated CO_2 emission cuts (Levy and Newell, 2000).

Environmental groups have a large impact on public opinion as their views are generally more trusted than those by industry and governments (Levy and Newell, 2000). Environmental groups tend to be divided between those that believe that in order to achieve useful reductions in CO_2 emissions CCS will be required, and those that believe that it is a fundamentally flawed technology that perpetuates our current use of fossil fuels and that a whole new system of renewable energy is needed. The first group of NGOs also believe that CCS may be the only way to engage the fossil fuel industry in a meaningful way (Meadowcroft and Langhelle, 2010). Some NGOs have become more positive about the prospects of CCS as an interim solution as long as it does not detract from more long-term solutions such as renewable energy (Meadowcroft and Langhelle, 2010). A transitional strategy where fossil fuel use with CCS is gradually replaced over the next century with less carbon intensive options could benefit both groups.

Since the release of the IPCC Special Report on CCS (2005), the scientific community has focused more strongly on CCS as a climate change mitigation strategy. CCS has been identified as a major option in a portfolio of mitigation actions need to address anthropogenic climate change. The scientific community has also provided strongly needed information about the risks and challenges facing CCS. Many collaborations between the scientific and fossil fuel community have been developed, allowing for more practical research (Meadowcroft and Langhelle, 2010).

The path of CCS development within countries has been varied, often in response to vested interests in fossil fuels and their approach to addressing climate change. There has been little movement on GHG emission reductions in Canada since the early 2000s. GHG emissions have risen significantly to be approximately 30% above the committed Kyoto targets of 558.4 MT and are at 692 MT as of 2010 (see Figure 57). As Canada already uses a substantial amount of hydropower, it was, and continues to be, much more difficult to reduce CO_2 emissions than those in the EU who had already been making the transition from coal to natural gas in the 1990s. These factors combined with increasing energy demand due to above average population growth and per capita GDP growth compared with the EU during the period 1990 – 2006 made achieving the Kyoto targets a very difficult task (Meadowcroft and Langhelle, 2010). Nonetheless, Canada has a history of breaking climate mitigation agreements (as do many other countries); it did not meet its 1988 G7 targets, the World Conference on the Changing Atmosphere, the 1992 agreement at the Rio Conference, or the Kyoto Protocol in 1997 (Meadowcroft and Langhelle, 2010). Although unsuccessful, Canada initiated six different policies on curbing CO_2 emissions to meet these targets.

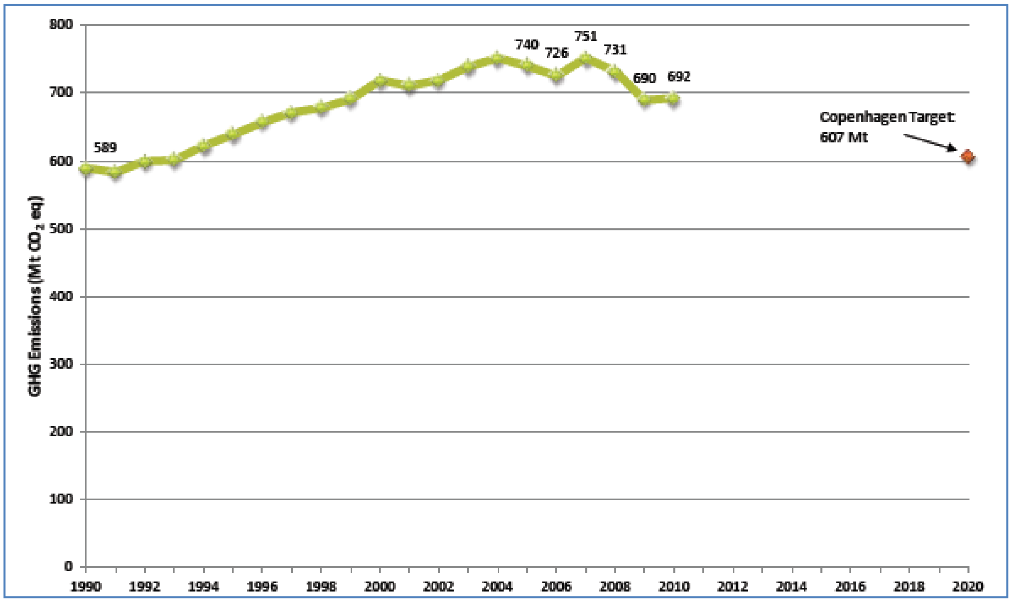

Figure 57 Canadian greenhouse gas emissions between 1990 and 2010 (Environment Canada, 2010)

There is renewed interest in emissions reductions with the Copenhagen conference held in 2009, wherein Canada indicated that it will replicate any scheme implemented by the U.S. (Global CCS Institute, 2009). The aim of harmonizing climate strategies with the U.S. is to avoid protectionist measures as the two countries are so economically connected. Prime Minister Stephen Harper reiterated this by commenting that we need a “continental approach” to climate change (Harper, 2010). After investing substantially in CCS research in February 2010 the U.S. created an Interagency Task Force on Carbon Capture and Storage. The goal of this Task Force was to develop a plan within 6 months to bring 5-10 commercial demonstration projects online by 2016 (The White House, 2010). Canada would need to follow suit proportionately, in order to keep pace with the U.S.

Canada currently has one provincial cap-and-trade system in Alberta. It came into force in 2007 and applies to all entities that emit more than 100,000 tonnes of CO_2 annually. The program allows emitters to reduce their emissions by purchasing CO_2 credits from an Alberta emissions reduction project. They also have the option of paying into an Alberta technology fund at a cost of 15$CAN/tonne. This fund effectively limits the price of trading and buying credits to below 15$CAN/tonne of CO_2 (Global CCS Institute, 2009). Currently the emissions standards are based on intensity targets with the aim of changing to 'hard', or non-intensity based caps, in the years leading up to 2050. They have (along with Quebec, Manitoba and Ontario) passed framework legislation that would allow for integration within a regional, national or international cap-and-trade program (Global CCS Institute, 2009).

British Columbia and Quebec have chosen a different path with their carbon tax. B.C. has imposed a tax on almost all fossil fuels with an initial cost of 10$CAN per tonne of CO_2 in 2008, which has increased by 5$CAN for each year to now reach $30CAN in 2012 (B.C. Ministry of Finance, 2012). Quebec introduced what it claims is North America's first carbon tax, targeting only transportation fuels. The tax adds 0.8c/litre onto the price gasoline and 0.9c/litre on diesel fuel (Global CCS Institute, 2009).

Canada does not mandate CCS in any of its provinces or territories nor is there any systematic program for developing and implementing CCS. There are many province-wide strategies promoting emission reductions, mostly in the form of renewable energy. None of these however, touch upon CCS (Global CCS Institute, 2009). There is also no federal law or policy regarding the liability of CO_2 leakage from geological storage. The Canadian Environmental Protection act has been amended however to designate GHGs as toxic substances. This amendment allows Environment Canada to establish limits on these gas emissions without further legislation (Global CCS Institute, 2009). The Alberta Ministry of Energy passed the Carbon Capture and Storage Statutes Amendment Act, 2010 to set out the rules and regulations of permitting CCS projects, and to address liability of storage (2010). This Act amends many previous Acts to allow for the permitting of CCS projects and sets out the requirements for operation and for closure permits where the government will then assume liability.

Despite the lack of policy supporting CCS in Canada there has been significant research conducted. The most notable project is the Weyburn-Midale project in Saskatchewan started in 2000. The objective of this project is to determine whether CO_2 can safely be stored for at least 5,000 years (Global CCS Institute, 2009). The Province of Nova Scotia has also been given funding with the goal of researching CCS technologies and its possible application to the province (Natural Resources Canada, 2008) (see the Carbon Capture and Storage Research Consortium of Nova Scotia for more information: (www.ccsnovascotia.ca/index.php).

In July 2009, the Alberta CCS Development Council released a report with recommendations for developing CCS within the province. As a result of this study 770$CAN million was awarded from the Alberta government for proposed CCS projects (Carbon Capture Journal, 2010). Several projects were initiated including one involving TransAlta Corporation and Alstom who signed an agreement to retrofit a TransAlta coal-fired power plant with Alstom's Ammonia capture technology. This project, dubbed Pioneer, was to be located west of Edmonton and was expected to reduce CO_2 emissions by 1 million tonnes per year at 3 different coal-fired power plants. (Global CCS Institute, 2009). Other projects, including the Pioneer project, have been cancelled or postponed due in large part to high costs of CCS and uncertainty around regulations. Three large-scale CCS projects in Alberta (Shells Quest project, Enhance Energy, and Swan Hills Synfuels) are still proceeding but have not fully committed to full implementation (Tait, 2012).

In addition to these pilot and demonstration plants, the Canadian federal government and the Alberta government have pledged to provide funds for deploying CCS technologies. In 2008 the Alberta government announced a 2$CAN billion fund to encourage the construction of early CCS projects within the province. More recently, through the 2009 Canadian Economic Stimulus Plan, 650$CAN million was proposed towards large-scale CCS projects (Government of Canada, 2009).

The responsibility of regulating the transport of CO_2 within a province resides within the jurisdiction of the provinces. To date there is no regulatory scheme in place for transporting CO_2. When pipelines cross provincial or federal borders, however, they become under the jurisdiction of the Federal government through the National Energy Board, Environment Canada and the Department of Natural Resources (Global CCS Institute, 2009). CO_2 is classified as a dangerous good under the Federal Transportation of Dangerous Goods Act and thus has specific safety compliance obligations.

The public does have direct say in the transport of CO_2, beyond public hearings through the National Energy Board Act. This allows the public to attend a certificate hearing where they may challenge the approval of a pipeline by requesting a further review of the approval. If that fails, a formal appeal may be filed with the Federal Court of Appeal (Global CCS Institute, 2009).

In early 2010 the Institute for Sustainable Energy, Environment and Economy (ISEEE) at the University of Calgary released a report on the opportunities for large-scale storage in central Alberta. The study found that more detailed drilling and mapping is required before large-scale injection can be commercialized. It was however concluded that there is likely enough storage capacity to ensure that there will be no physical constraint to scaling up CCS in Alberta (Lavoie and Keith, 2010). Major outstanding issues include a lack of reservoir data on the extent of storage in Canada, and more detailed knowledge is needed to manage reservoir fluid pressures during and after injection of CO_2. The costs of injecting and storing CO_2 in Western Canada are expected to be in the range of \$3/tCO_2.

As the second largest country in the world, Canada possesses a wide range of energy sources and potential storage locations. The Western Canadian Sedimentary Basin, located mostly in Alberta and Saskatchewan is widely acknowledged as an ideal site for storing CO_2 (see Figure 58 and Table 30) (Meadowcroft and Langhelle, 2010). Many of the large stationary emitters of CO_2 (coal-fired plants) are located in this basin as it is also rich in fossil fuels, thus most of the CCS development in Canada is focused in this area. Fossil fuel development in Alberta is expected to greatly expand, especially in the oil sands. Emissions from this development may grow to equal Canada's current total emissions by the year 2050. Developing CCS would therefore require an extensive network of pipelines (or 'CO_2 backbone') to transport the CO_2 (Meadowcroft and Langhelle, 2010). The Integrated CO_2 Network (ICO2N) has proposed a plan to fund, design and build this network of pipelines in western Canada.

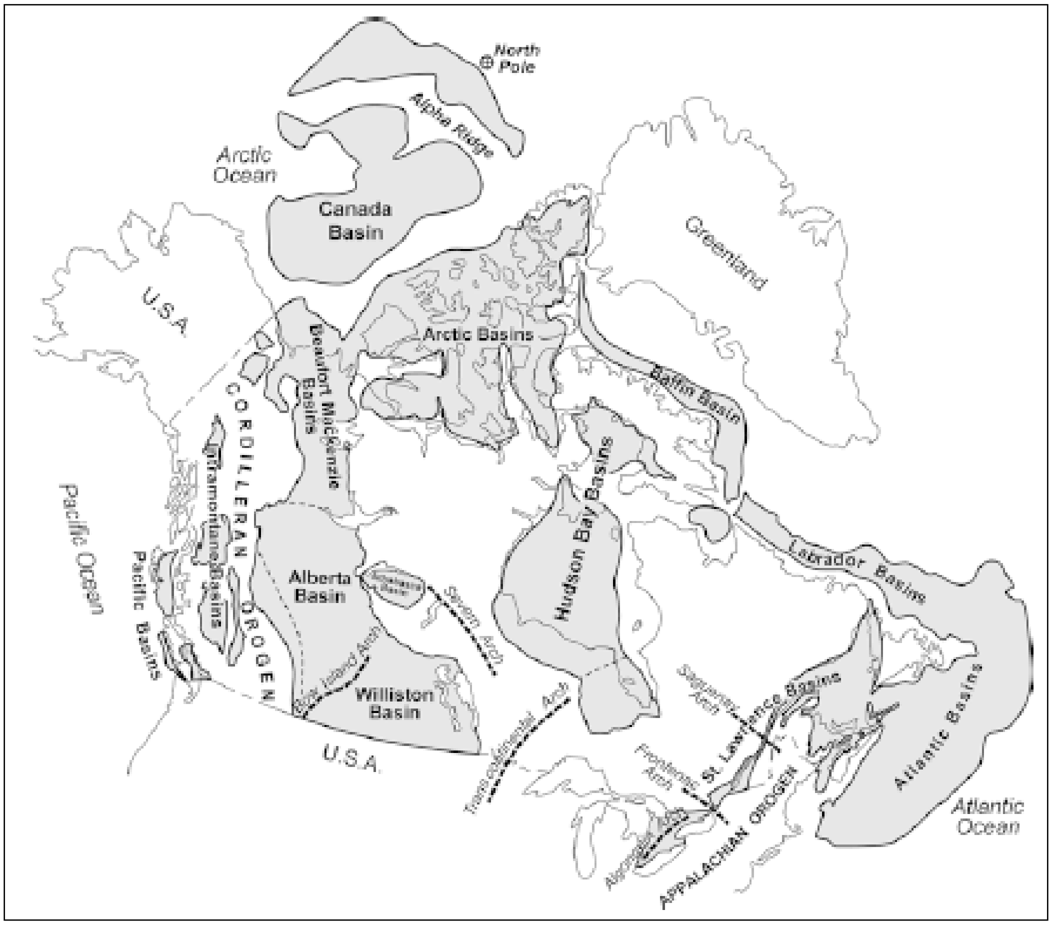

Figure 58 Distribution of sedimentary basins in Canada (Bachu, 2003)

Table 30 Ranking of Canada's sedimentary basins based on suitability for CCS (Bachu, 2003)

Rank	Basin(s)	Characteristics	Score
1	Alberta	Foredeep, giant, deep, mature, coals and salts, good infrastructure, temperate, large point CO_2 sources, large CO_2 emissions	0.96
2	Williston	Intracratonic, large, deep, mature, coals, good infrastructure, temperate, large point CO_2 sources	0.88
3	Beaufort-Mackenzie	Foredeep, large, deep, exploring, sub-arctic, large hydrocarbon potential	0.60
4	SW Ontario	Arch, shallow, small, over mature, good infrastructure, temperate, CO_2 sources	0.52
5	Atlantic shelf	Offshore, developing, oil and gas, coals, large CO_2 point sources	0.35
6	St. Lawrence River	Foredeep, small, temperate, CO_2 sources, no hydrocarbons and coals	0.31
7	Gulf of St. Lawrence	Offshore, small, no CO_2 sources	0.26
8	Arctic islands	On/offshore, arctic, coals, no CO_2 sources and infrastructure	0.24
9	Intramontane	Convergent, small, coals, no CO_2 sources and infrastructure	0.20
10	Hudson Bay	Mostly offshore, intracratonic, sub-Arctic, no potential, no CO_2	0.18
11	Eastern Arctic	Offshore, arctic no potential, no CO_2 sources	0.13
12	Pacific	Convergent trench, offshore, unexplored, no CO_2 sources, no infrastructure	0.09

Canada has a relatively weak federation in which the provinces control much of the natural resources that lie within their borders. There are strong tensions between the western provinces that own large reserves of fossil fuels, and the provinces in the east that hold much of the power in the country. With the oil shocks in the 1970s this came to the fore with the National Energy Program (NEP) which took some control and money away from the oil producing provinces and gave it to the federal government (Meadowcroft and Langhelle, 2010). The NEP allows Canada to reduce its CO_2 emissions while allowing Alberta and Saskatchewan to develop their fossil fuel resources. This dual purpose is why Alberta's climate change strategy almost exclusively relies upon CCS, and the National Roundtable on the Environment and the Economy strongly support CCS (Meadowcroft and Langhelle, 2010).

One of the possible future uses of CCS is through direct air capture of CO_2. This technology is in the very early stages of research and will not be available for many years. This technology would in effect decouple the source of emissions with the capture technology allowing for these projects to be built at the site of storage thus negating transportation costs (Keith *et al.,* 2006). Direct air CCS could also allow for net negative emissions, resulting in atmospheric concentrations of CO_2 to not only slow down but to actually decrease (Meadowcroft and Langhelle, 2010). The main obstacle is that atmospheric concentrations of CO_2 are 100 times lower than those from flue gases and are thus much more expensive to treat. These techniques may also be used in remediation actions from slow geological leaks.

Appendix 2A Decision Analysis

This appendix provides a further description of decision analysis tools that were considered, but not used within the thesis. It provides a context of other methods with which to compare the proposed methodology. Many of the methods rely on similar theories and use some tools in common but are not designed to address CCS decisions specifically.

There are many methods to measure the criteria on scales that can be compared and to weight the relative importance of each criterion (which we call preferences). The attributes and factors by which alternative CCS projects are compared are referred to as criteria. Throughout this thesis, alternative CCS projects are also referred to as options.

2A.1 DECISION ANALYSIS METHODS

2A.1.1 Value Measurement Models

Value measurement model is a numerical method that covers several types of methods and is used to provide structure to incorporating the views of decision makers (DMs). In these methods, DMs provide criteria data, after which a preference or ranking of the criteria can then be made. DMs then assign weights to the criterion representing the criterion's contribution to the final score. The criteria weights should indicate how much the DM is willing to accept when comparing two alternative choices (Belton and Stewart, 2002). Usually the weights are assigned on a percentage scale. Expert opinion and best available data are usually used, especially in a variant of this method called Analytical Hierarch Process (AHP) (described in Section 2a.1.2) (Munier, 2004).

The most popular value measurement model is an additive value function or multi-attribute value theory (MAVT). The popularity of MAVT is in part due to its simplicity and limited time requirements. The method is ordinal, and thus can only be used to rank the order of preference between alternatives, not the relative preferences between alternatives (Ramanathan, 2004). This method uses the following generic equation:

$$V(\mathrm{a}) = \sum_{i=1}^{m} w_i v_i\,(a) \qquad \text{Equation 2}$$

Where V is a numerical value assigned to each alternative, $v_i(a)$ is a partial value function representing the alternative projects' scores on criterion i. w_i is the assigned weight of each alternative and represents its contribution to the total score. A normalized scale such as 0-100 is needed (Løken, 2007). The option with the highest score (V(a)) would then be the preferred choice.

Keeney and Raiffa proposed a modification of the MAVT approach, called multi-attribute utility theory (MAUT) (1974). The MAUT approach adds a risk element to MAVT functions. In this method, the risk preferences of the DM (how risk averse they are) must be established instead of the value functions. The MAUT approach is more complicated and time consuming than the

MAVT method and involves attempting to model the DM's attitude to risk (Ramanathan, 2004). MAUT is cardinal in that the alternatives can be measured not just by rank but also by how much preferred one alternative is relative to another alternative.

2A.1.2 Analytical Hierarchy Process

Analytical Hierarchy Process (AHP) is one of the most popular multi-criteria methods in use (Ramanathan, 2004). AHP is a method very similar to MAUT and results in a value function. AHP however was developed independently of MAUT by mathematician Thomas Saaty and is based on different assumptions about value measurements (Løken, 2007). Due to these differences, some argue that AHP is not a true value function method. Nevertheless, since both methods produce a score in which a higher value is more desirable, the results from the two methods can be directly compared (Løken, 2007). AHP does not produce a unique solution; rather it produces a prioritized set of projects or alternatives.

The theory used in AHP is that a DM can reduce a complex problem into a hierarchy with an objective at the top of the hierarchy followed by criteria and sub-criteria at subsequent levels. At the bottom of the hierarchy lies the decision alternatives (Pohekar and Ramachandran, 2004). The process involves a series of pair-wise comparisons in which criteria are rated on a semantic scale using a system of preferences such as those displayed in Table 31. The ratings are based on the DM's relative preference with respect to the elements at the next higher-level. The outputs from these rankings are formed into matrices where an overall ranking of each alternative on each criterion is made. As the math is complex, computer programs are used to perform the calculations (Løken, 2007). The values from the pair-wise comparisons are affected by the criteria weights that are decided beforehand. After these values are compiled in the matrices, a ranking called the Global Priority is represented in a column vector (Munier, 2004).

Table 31 Fundamental scale for the Analytical Hierarchy Process comparisons of alternatives (Løken, 2007)

1	Equally preferred
3	Weak preference
4	Strong preference
7	Very strong or demonstrated preference
9	Extreme importance
2,4,6,8	Intermediate values

Some of the benefits that make AHP analyses so popular are its simplicity, flexibility and intuitive procedure. AHP is also able to handle heterogeneous units and quantitative and qualitative data (Løken, 2007 and Ramanathan and Ganesh, 1995). The process does not require complicated modeling or computer algorithms, so no particular expertise is needed to perform the methods.

One of the major drawbacks to AHP is that it can be time consuming when there are many criteria or alternatives, which is often the case with large-scale energy decisions. The lengthy analysis is due to the number of DM's judgements needed to ensure consistency. For instance to evaluate eight criteria, 28 judgements are required (Ramanathan, 2004). There is some debate over whether the ranking preference table (see Table 31) also tends to over-emphasize the true differences between preferences (Huizingh and Vrolijk, 1997). The verbal scale of 1–9 is arbitrary and therefore has no scientific foundation. There is no analytical reason why a 9 should be used for a given preference instead of 7, 11 or another number. (Barzilai, 2008)

Another problem with AHP occurs when using expert opinion; experts need to be knowledgeable in many areas in order to properly assign weights. Experts disagree about the importance of criteria and have different values due to their different backgrounds and biases. The need for expert DMs is especially problematic with large complex problems that span many disciplines and specifically in the social sciences. One way to help solve this problem is to compare all alternatives and give the alternatives an importance on a scale such as 0-1. Relative weights can then be added to these values as they are all on the same 0-1 scale (Munier, 2004). Another major problem is that the preference ranking order of the alternatives can be changed or even reversed if another alternative is added during an AHP analysis. One way to avoid criteria rank reversal is to ensure that all alternatives are included in the initial assessment; however in practice this is not always possible (Ramanathan, 2004).

2A.1.3 Goal, Aspiration and Reference Level Models

Goal programming, aspiration level, and reference level models are often grouped together and abbreviated as goal programming (GP). These methods tend to be used to eliminate the least favourable options before a more rigorous method is employed (Løken, 2007). The earliest multi-criteria method developed was the goal programming model, developed in the 1950s as an extension of linear programming (Ramanathan, 2004). The two most common methods are STEM and TOPSIS.

The step-method (STEM), allows for a direct comparison between alternatives, which helps highlight the impacts of the DM's preferences on the decisions. Directly comparing alternatives can help reduce unintentional skewing by the DM (Løken, 2007). The TOPSIS method is also quite simple; however, it requires the DM to be involved in each step to precisely define their goals, which can be inconvenient and time consuming.

These methods are straightforward and less subjective than MAUT and MAVT theories because they are conducted directly using one-by-one comparisons of the options. There is a significant amount of criticism however regarding the process of assigning weights and normalizing variables (Løken, 2007). GP methods are generally only able to handle quantitative data, so it must be combined with other methods when qualitative data is used.

2A.1.4 Outranking Models

Outranking models are similar to MAUT models in that each alternative is ranked pair-wise based on each criterion. The model determines by how much each alternative outranks another. There are two common versions of outranking models (also referred to as the French school of MCDA): ELECTRE and PROMETHEE (Løken, 2007).

The elimination and choice translating reality method (ELECTRE), like most models, has been modified over time and now the third version (ELECTRE III) is the most popular method used in energy planning after AHP (Pohekar and Ramachandran, 2004), although there are even newer models now. ELECTRE is able to assess both qualitative and quantitative criteria. It places an emphasis on avoiding very poor scores by removing individual criterion even if that alternative has a high overall score. The emphasis on evaluating and removing criteria with poor scores allows for the use of thresholds beyond which the option is unacceptable (Løken, 2007). For example, one project comprising many criteria may have an unacceptably high risk of health problems resulting in a low score on that criterion. Regardless of how well the alternative scored overall, it would be excluded due to its unacceptable low score on health. From these thresholds, concordance and discordance indices (degrees of agreement between criteria scores) can be calculated. Concordance and discordance indices lead to strong and weak relationships between the criteria and then to a ranking of the alternatives (Tsoukias *et al.,* 2002). Similar to the GP methods, ELECTRE is not always thorough, but is often used to determine a short list of the most favourable alternatives to be analysed further with another decision analysis method (Løken, 2007).

The preference ranking organizational method for enrichment evaluation (PROMETHEE) method also uses a pair-wise ranking of alternatives to determine a preference function for each criterion. The six generalized criterion functions most often used are: usual criterion, quasi-criterion, criterion with linear preference, level criterion, criterion with linear preference and indifference area, and Gaussian criterion (Pohekar and Ramachandran, 2004). The method involves a preference function where the function represents the difference in preference between two alternatives for any criterion. A preference index is then developed from which a value outranking relation is made. A value outranking relation produces an overall ranking for each alternative (Løken, 2007). The first step in the process is to develop the preference function. A preference function is an adjustable equation that evolves as people's preferences change with time and increased information. Once the pair-wise comparisons are completed, they are tabulated into a matrix and then thresholds are determined. The PROMETHEE software is then employed to rank each other alternative (see Figure 59) (Tsoutsos *et al.,* 2009).

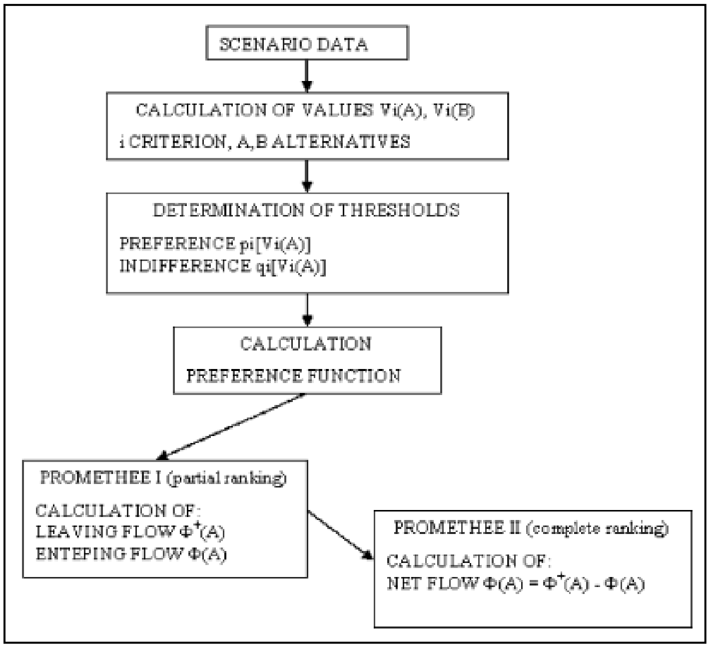

Figure 59 Flowchart for a decision analysis using PROMETHEE (Tsoutsos *et al.,* 2009)

Huang and Yoon developed the Technique for Order Preference by Similarity to Ideal Situations (TOPSIS) in response to deficiencies in the ELECTRE method (1981). The technique is based on the principle that the selected alternative should have "the [longest] distance from the negative ideal solution in geometric sense. The preference orders are compared based on their

Euclidean distances to the ideal and or negative ideal solution" (Pohekar and Ramachandran, 2004). This method aims at choosing the least bad option. TOPSIS allows for group decision making as well as the use of thresholds (Mojtahedi *et al.,* 2008).

2A.1.5 Preference Function Models

Preference function models aim to develop an easy way of extracting preference information from DMs. Utility-based preferences are typically measured on interval scales and do not have a natural origin and are thus arbitrary and subjective. In preference function modelling, a different interval scale is used in which the best criterion (most preferred by the DM) is assigned a value of 100 and the worst a value of 0. The intermediate alternatives are then assigned values in between. The interval scale is then determined through a series of linear system equations (Tamura *et al.,* 1999). A two dimensional preference curve is shown in Figure 60. Each axis represents a different criterion with each dot representing one alternative's score on the criterion. The preference function is expressed as an indifference curve between the two axes going through the alternative's dot. The theory suggests that a DM would be indifferent if the alternative were located anywhere on the indifference curve.

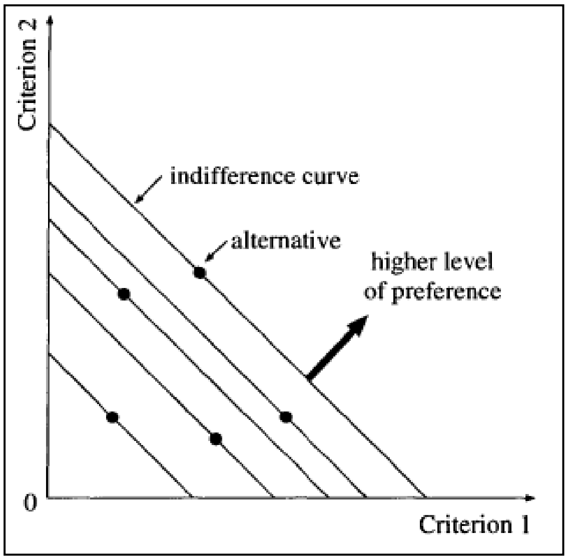

Figure 60 Two dimensional indifference curve for alternatives and two criteria (Tamura *et al.,* 1999)

Preference function modeling resolves the problem of having no natural zero for most decision criteria by using a ratio formula for preference of $(x_1 - x_2)/(x_3 - x_4)$ instead of x_1/x_2 as is the case with many MCDA methods. For instance, although one criterion may have a very low score or preference, the DM is unlikely to give the criterion a score of absolute zero; however, if that were the case, then it cannot be compared to any other alternative in a meaningful way since multiplying it by any number or weight will not change its value. Using ratios and the logarithm scale, which does not allow for zeros, resolves this problem. Subsequently a series of calculations are made including taking the logarithm in which the goal is to minimize x (Tamura *et al.,* 1999). Weights are determined using a marginal rate of substitution.

Factor Analysis is a method used to minimize the number of criteria needed in a study without sacrificing the quality of the results. Factor analysis is a statistical technique used to determine the underlying structure of a set of data (Munier, 2004). The process attempts to determine the interactions and correlations between criteria to ensure that criteria are not counted twice under slightly different processes. When there are two factors that result in the same event (for example vehicle speed and driver attentiveness which can both impact vehicle accident rates) it can be determined that there is an underlying reason, in this case driver tiredness is involved in both processes which is not immediately apparent (Munier, 2004). In this example, a decision analyst would try to gauge driver tiredness and use that as a criterion instead of using both vehicle speed and driver attentiveness, reducing the amount of data needed to be collected.

Appendix 2B Stakeholders and Potential CCS Issues

As the risk model has been designed to accommodate a wide range of decision makers, it is instructive to consider potential users. This appendix outlines the major stakeholder groups that could be involved in a CCS project. Each stakeholder group has some power to help or hinder the development of CCS through direct legislation or through lobbying. Each group also has specific CCS issues that they are concerned with. These aspects are outlined below.

Stakeholder	**Decision Power**	**Issues**
Federal government	-Emission/ transportation/ storage legislation -Liability -Investment -Mandate/ ban CCS	-Liability -Public pressure -Economic competitiveness/ jobs -Environmental protection
Provincial government	-Emission legislation -Liability -Investment	-Liability -Public pressure -Economic competitiveness -Environmental protection
Municipal government	-Zoning -Funding	-NIMBY -Environmental protection
Concerned citizens	-Public opposition/support	-NIMBY -Leakage -Environmental protection
Utilities	-Where to implement CCS -When to implement CCS	-Cost -Fuel supply -Integration into grid
Environmental groups	-Lobbying -Media -Advocacy	-Environmental damage (acid rain, mining, leakage, future impacts)
NGOs	-Lobbying	-Ethics -Environmental impacts
Employment seekers		-Jobs
Private companies	-Lobbying -Funding projects	-Business opportunities
Universities	-Funding research	-Research opportunities
Petroleum companies	-Research technologies -Implement projects	-Enhanced oil recovery -Enhanced coal-bed methane

Appendix 2C Criteria that can Impact the Development of CCS

CCS is a large and varied technology with many potential impacts. There are also a substantial number of factors that can affect CCS. These can be divided into business/technical and exogenous risks. Understanding the risks, the best and worst cases, who is impacted and what can be done to mitigate risks is important to developing CCS. These risks are outlined below and were prepared for the September 8th 2010 conference on risk management held in Calgary by Carbon Management Canada.

Business/Technical Risks

Type of risk	**Variable**	**Best case**	**Worst case**	**Other issues**	**Who/what is impacted**	**Mitigation**
Physical	Offshore CO_2 storage potential	-Large potential	-Limited potential	-see Section 2.3	-Utilities, CCS developers	-Push for more CCS research and pilot projects
	Distance to CO_2 storage sites	-There are many sites near power plants	-Few sites far from generation sources		-Utilities, CCS developers	-Push for more CCS research and pilot projects
	Environmental externalities of CO_2 (increased fuel use, SOx emissions)	-Are limited due to improvements in CCS	-Are significant	-Environmental legislation	-Utilities, CCS developers	-Increase efficiency of CCS
	CO_2 leakage (reservoir or pipeline)	-Is not significant	-Is significant		-Utilities, CCS developers	-Push for more CCS research and pilot projects
	Storage availability (pore space)	-Is significant and accessible	-Is not significant	-Injection rates -Risk of needing to abandon storage site	-Utilities, CCS developers	-Push for more CCS research and pilot projects
	Coal reserves	-Are large	-Are smaller than expected		-Utilities, CCS developers	
Environmental	Environmental protection pressure	-Is positive towards CCS	-Rallies against CCS	-Climate change becomes more well understood and certain	-Public, environment	-Increase awareness of CCS benefits
	Conservation trends	-Decreases or is slow	-Increases substantially		-Public, environment	
Engineering	Rates of technological learning for CCS	-Is fast	-Is slow		-Utilities, CCS developers	-Increase CCS research

	Infrastructure	-Ability to integrate into current grid and infrastructure	-Inability or limited ability to integrate	-Scale is very important		-Increase research into smart grids
Economic	Coal/Natural gas prices	-Are stable or low	-Fluctuate or increase	-Alternative fuel sources	-Utilities, CCS developers	-Invest in improved CCS efficiency
	Alternative energy production sources	-Are not competitive with CCS	-Improve dramatically	-Energy trends, new technology	-Utilities, CCS developers	-Increase CCS research

Exogenous Risks						
Type of risk	**Variable**	**Best case**	**Worst case**	**Other issues**	**Who/what is impacted**	**Mitigation**
Economic	Oil prices	-High oil price but low coal price will push CCS development	-Low oil price will encourage oil consumption -High oil and coal prices will encourage conservation and renewables	-Altered oil demand -Uncertain demand -Difficulty planning	-Utilities, CCS developers	-Use a variety of fuels, sign long term contracts
	Natural gas prices	-High oil price but low natural gas will promote natural gas CCS and slow coal CCS -High natural gas prices will promote coal CCS	-High natural gas will promote conservation	-Effects will vary -High prices will encourage coal CCS but discourage Nat Gas CCS as well as conservation and vice versa	-Utilities, CCS developers	-Use a variety of fuels, sign long-term contracts

	Peak oil	-Encourage abundant coal CCS	-More impetus to conserve and move to renewables	-All materials become more expensive	-Utilities, CCS developers	-Use a variety of fuels, sign long term contracts
	Cost of CCS technology	-Improve dramatically	-Do not improve	-Materials cost, technological improvements, legal and regulatory costs	-Utilities, CCS developers	-Increase research into lowering the cost or improving efficiency
	Carbon tax	-CCS is included as an option for reducing CO_2	-Not included or uncertain	-Cap and trade	-Utilities, CCS developers	-Lobby for action
Political	International agreements	-Require CCS -Set emission targets that will in effect require CCS	-Prohibit CCS, especially ocean storage	-Increase public knowledge	-Public, government, utilities, CCS developers	-Lobby for action
	Carbon markets	-Help promote options including CCS -Carbon offset options	-Could promote other options, reducing the need for CCS	-Depends on whether CCS is included as a valid option	-Public, government, utilities, CCS developers	-Lobby for action
	National/provincial legislation	-Goals are extended and enforced	-Goals are not extended or not adequately enforced	-Other governmental precedent	-Transboundary pipelines, legal teams	-Lobby for action
Legal	Post injection liability issues	-Leakage turns out not to be a significant issue	-Leakage is significant	-Who owns the CO_2?	-Costs	-Lobby for action
	Pore space ownership	-Is clear	-Not addressed			-Lobby for action
Alternative energy source	Developments in wind technology	-Slower than expected	-Faster than expected	-Rate of technological change, costs	-Public, government, utilities, CCS developers	-Push for more CCS research

development	Development in solar technology	-Slower than expected	-Faster than expected	-Rate of technological change, costs	-Public, government, utilities, CCS developers	-Push for more CCS research
	Developments in tidal technology	-Slower than expected	-Faster than expected	-Rate of technological change, costs	-Public, government, utilities, CCS developers	-Push for more CCS research
	Developments in nuclear technology	-Slower than expected	-Faster than expected	-Rate of technological change, costs	-Public, government, utilities, CCS developers	-Push for more CCS research
	Hydro energy	-Already at max capacity or declines requiring more CCS	Opportunities to expand	-Rate of technological change, costs	-Public, government, utilities, CCS developers	-Push for more CCS research
	Geothermal energy	-Develops slowly	-Is able to contribute significantly to energy supply	-Rate of technological change, costs	-Public, government, utilities, CCS developers	-Push for more CCS research
	Enhanced oil recovery	-Many opportunities	-Limited potential	-Altered oil reserves	-Public, government, utilities, CCS developers	-Push for more CCS research
	Enhanced coal-bed methane	-Many opportunities	-Limited potential	-Altered methane reserves	-Public, government, utilities, CCS developers	-Push for more CCS research
Social	Public Perception	-Is positive	-Is negative	-Cost of energy	-Public, utilities, government, CCS developers	-Increase awareness of CCS
	NIMBY	-Minimal NIMBY	-Significant NIMBY	-Cost of energy	-Public, utilities, government, CCS developers	-Increase awareness of CCS
	Energy demand	-Increases	-Decreases			

Appendix 2D MCDA Case Study

A case study is present below in order to illustrate some of the theory used in MCDA methods. A study titled "Sustainable energy planning by using multi-criteria analysis application in the island of Crete" (Tsoutsos *et al.,* 2009) was chosen due to its similarity to the problem of assessing CCS decisions. A summary of the study is shown below.

2D.1 BACKGROUND

Crete is one of largest islands in the Mediterranean. It has experienced a period of rapid economic and population growth in part due to increased tourism. The rapid growth has resulted in increasing energy demands that are coupled with the need to reduce its environmental footprint (Giatrakos *et al.,* 2009). In order to accommodate the increasing energy needs and limit the impact on the environment, several different renewable energy sources (RES) have been proposed. It has been determined that 30% of the total energy required by Crete could come from RES (Tsoutsos *et al.,* 2009).

The authors use a multi-actor, multi-interest (multi-stakeholder), multi-criteria decision analysis framework for their energy problem. They chose this method as it allows the input of quantitative and qualitative data, it allows for multiple actors (stakeholders) and it is a well accepted method that is inclusive and objective (Sigrid, 2004). The weaknesses with respect to subjectivity of weighing the criteria and translating qualitative data are noted. The PROMETHEE I and II methods for ranking criteria were used for the study (see Appendix 2A1.4).

2D.2 MCDA PROCESS

Since the relevant criteria were already chosen by the authors, the first step of their analysis is to calculate the preference function for every criterion. From the preference function of criteria, a preference index is created. The alternatives are then compared in pairs. The outcomes are displayed in an evaluation matrix. Indifference and preference thresholds are then used to express the DM's preference for each criterion. The threshold process involves assessing at which point a DM would be indifferent or would prefer an alternative through the use of weightings. The PROMETHEE I and II methods are then used to rank the alternatives. Figure 61 outlines the full procedure for the MCDA in this study (Tsoutsos *et al.,* 2009).

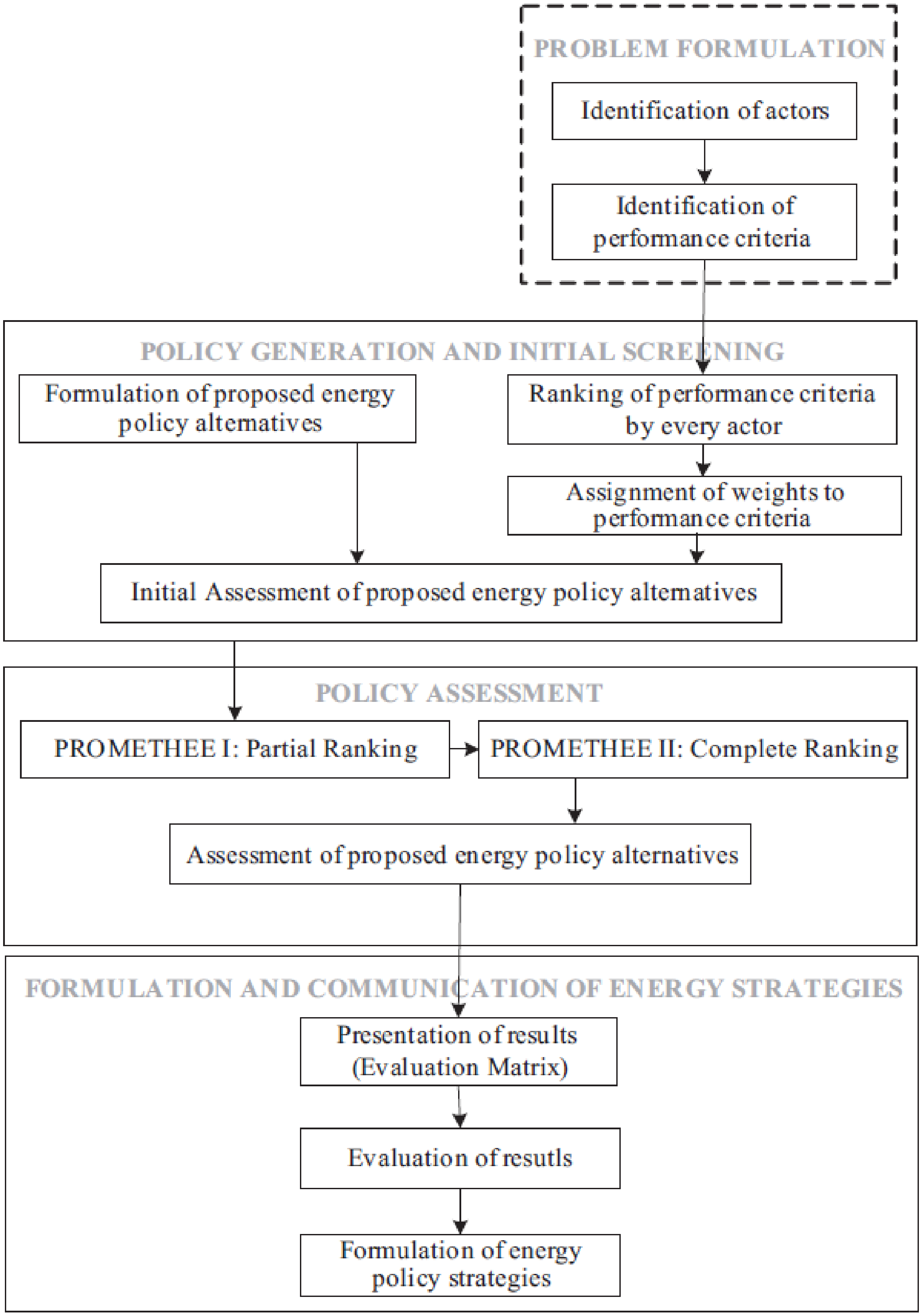

Figure 61 Applied procedure for the MCDA sustainable energy planning study in Crete (Tsoutsos *et al.*, 2009)

2D.2.1 Stakeholders

In order to evaluate the alternatives, the authors chose a variety of stakeholders including: local authorities (LA), potential investors (PI), local communities (LC), academic institutions (AI), environmental groups (EG) and government and European Union (EU). Industrial partners were not included due to their lower influence in the development directions of Crete (Tsoutsos *et al.,* 2009).

2D.2.2 Evaluation Criteria

The authors chose seven criteria, of which four are techno-economic and three are socio-environmental. The criteria are: investment, operation and maintenance cost, conventional fuel savings, maturity of technology, safety (security) of supply, CO_2 emissions avoided, contribution to local development and welfare, and social acceptance and viability of the remaining environmental effects (Tsoutsos *et al.,* 2009). Each of the criteria (Ci) is described briefly below.

2D.2.2.1 C1, Investment, Operation and Maintenance Cost (€)

The investment, operation and maintenance cost criterion includes all the investment costs, physical construction as well as all the salaries and maintenance costs. Although the cost is expressed in Euros, it is not clear how this is estimated and calculated. Usually all the costs are converted to a net present value, although again the method used is not shown and the discount rate can have a significant impact on the outcome if alternatives have different project timelines.

2D.2.2.2 C2, Conventional Fuel Savings (kg/yr)

Conventional fuel savings is the amount of fuel (in kg/yr) that would otherwise be used in power generation plants if the RES were not developed.

2D.2.2.3 C3, Maturity of Technology

This criterion refers to the reliability of each proposed technology as well as its saturation level (pervasiveness) in the domestic and European market. In this case it is assumed that a higher reliability and saturation is better than a lower one. Although a low maturity rate will likely result in greater improvements over time, only some of those improvements can be incorporated into a technology installed now. The categories and their rankings are shown in Table 32.

Table 32 Values of the different levels of maturity used in this study (adapted from Tsoutsos *et al.,* 2009)

Condition of technological artefact	**Value of C3**
Technologies in laboratory and research stage	1
Technologies of pilot programs	2
Technologies that require further improvements in order to increase their efficiency	3
Commercially mature technologies with solid place in the wide domestic market	4
Commercially mature technologies with solid place in the supranational and European market	5

2D.2.2.4 C4, Safety (Security) of Supply

Safety of supply is used to determine how well an energy technology can fit into the existing electricity grid. Many RES are intermittent (e.g. photovoltaic cells only produce electricity during the day; wind turbines only produce electricity when the wind blows at a specific speed). The higher the level of intermittency, the less well that technology can be integrated into the grid. The scale used in this analysis for safety of supply is shown in Table 33.

Table 33 Qualitative safety (security) of supply scale for renewable energy sources (adapted from Tsoutsos *et al.,* 2009)

Frequency of interruptions	**Value of C4**
Activity of high discontinuity	1
Activity of mediocre discontinuity	2
Activity of retained discontinuity	3
Activity of low discontinuity	4
Continuous and stabilised activity	5

2D.2.2.5 C5, CO_2 Emissions Avoided (kg/yr)

CO_2 emissions avoided represent the amount of CO_2 emissions avoided due to the introduction of renewable energy sources. This is expressed in kg/yr of CO_2 avoided.

2D.2.2.6 C6, Contribution to Local Development and Welfare

Contribution to local development and welfare is another qualitative criterion representing the total social and economic impact of the alternatives on the regions surrounding the RES. The expected impacts are: creation/offer of workplaces, new chains of enterprises for energy supply, emerging enterprises in the energy sector, new industrial regions, and others (Tsoutsos *et al.,* 2009). The scale used to measure the contribution to local development and welfare is shown in Table 34.

Table 34 Qualitative scale used to measure the contribution to local development and welfare (adapted from Tsoutsos *et al.,* 2009)

Level of impact on local community	**Value of C6**
Null impact on the local community	1
Feeble impact on the local community	2
Mediocre impact on the local economy	3
Medium to high impact on the local economy	4
Very high impact on the local economy	5

2D.2.2.7 C7, Social Acceptance and Viability of the Remaining Environmental effects

This criterion indicates the public's opinion or acceptance to the proposed alternatives, such as storage site location options. This criterion includes issues such as noise, visual impacts and odours. Table 35 shows the scale used to evaluate the social acceptance (Tsoutsos *et al.,* 2009).

Table 35 Qualitative scale used to evaluate the social acceptance of the alternative energy scenarios in Crete (adapted from Tsoutsos *et al.,* 2009)

Societal context	**Value of C7**
The majority of residents are against any installations	1
The opinion of the population is divided	2
The majority accepts the installations, since they are located away from residential areas and at the same time there is no visual harm	3
The majority accepts the installations, since they are located away from residential areas, no matter if there is optical contact or not	4
The majority is in favour of the installations	5

2D.2.3 Criteria Weighting

Each of the stakeholder groups were asked to rank the criteria based on their subjective relative importance. Numerical weights were determined using the calculations shown in Table 36 below.

Table 36 Calculations used in determining the weighting for each criterion for each stakeholder (adapted from Tsoutsos, *et al.,* 2009)

Level of preference	r-level criteria	Number of r-level criteria	Weight	Means weight	Relative weight
1	C4, C5	2	6-7	6.5	23.2
2	C7	1	5	5	17.9
3	C1, C2, C3	3	2-3-4	3	10.7
4	C6	1	1	1	3.6
Total sum				100	

From these calculations a matrix was created showing all the weights for each criterion by the stakeholders. The matrix of stakeholder weights is shown in Table 37. The criteria correspond to the columns, whereas the six stakeholders are listed down the left hand side. The scores are all relative and add up to 100 for each stakeholder.

Table 37 Weights matrix for all the stakeholders/DMs (reproduced from Tsoutsos *et al.,* 2009)

Stakeholder	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**
IA	3.6	10.7	7.1	14.3	23.2	17.9	23.2
PI	25	7.1	21.4	17.9	10.7	3.6	14.3
PO	14.3	7.1	3.6	17.9	10.7	23.2	23.2
AI	10.7	10.7	10.7	23.2	23.2	3.6	17.9
EG	3.6	21.4	7.1	10.7	25	16.1	16.1
EU	19.6	19.6	5.4	5.4	19.6	19.6	10.8

2D.2.4 Energy Policy Alternatives

The authors presented four energy policy alternatives for the stakeholders to choose from and evaluate. Each energy alternative was made up of RES in order to meet a predetermined amount of energy (and renewable energy). The four policies were: install only wind farms; install wind farms and photovoltaic cells; install wind farms, photovoltaic cells and four olive kernel units; and install wind farms, photovoltaic cells and use oilstone biomass. Each alternative relies heavily on wind turbines to produce the majority of the renewable energy in part due to its low price and its ability to easily scale up supply. Each of the alternatives will be briefly discussed below.

2D.2.4.1 Installing only Wind Turbines

This policy alternative involves using only wind turbines in the form of wind farms to produce the required renewable energy supply. This policy would involve installing 63 2-MW turbines in high velocity wind regions. The turbines collectively would produce an estimated 376.6 GW/yr (Tsoutsos *et al.,* 2009).

2D.2.4.2 Installing Wind Turbines and Photovoltaic Panels

This energy policy alternative involves producing 95% of the renewable energy from wind turbines. The remaining 5% would come from photovoltaic panels. Sixty wind turbines would be used and a minimum of 103 m^2 of surface would be covered by solar panels.

2D.2.2.5 Installing Wind Turbines, Photovoltaic Panels and 4 Olive Kernel Units

In this energy policy alternative, 86.2% of the energy is derived from wind turbines. Photovoltaic panels provide 5% of the energy needs. Four olive kernel wood units capable of producing 10MW at a time for an annual energy supply of 55GW would provide the remaining 8.8% of the renewable energy supply. During olive processing, olive kernel wood is produced and is used for heat generation.

2D.2.2.6 Installing Wind Turbines, Photovoltaic Panels and Oilstone Biomass

The final energy policy alternative involves producing 75% of the energy needs through installing wind turbines. The remaining demand would come from photovoltaic panels (14%) and oilstone biomass (as a substitute for lignite coal) (11%). The oilstone biomass portion would comprise five units producing 10MW at a time for a total annual energy production of 55GW.

The discrepancy between the 55GW/yr in this alternative contributing 11% of the total, whereas in the previous alternative the 55GW/yr from the olive kernel units only contributed 8.8% of the total is due to the different overall energy production. Although each alternative has a similar overall energy production, there are small differences in the amount of energy provided by each technology that would likely impact their scores and overall energy production. It is not clear why the authors did not scale up some of the energy technologies so that each alternative would produce the identical amount of energy.

2D.2.2.7 *Alternative Rankings*

To evaluate the quantitative and qualitative data, the authors relied on previous studies (which they omitted). Once all the data are entered into PROMETHEE and combined with the stakeholder weightings, a series of rankings are produced. Figure 62 displays the results from the perspective of one of the stakeholder groups (Academic Institutions). PROMETHEE involves two steps in this study (although there can be more) – PROMETHEE I and PROMETHEE II. The process does not produce an ideal overall solution. It simply provides the optimal solution for each stakeholder. A further step could be taken in which the rankings of each stakeholder are weighted and added to produce combined ranking.

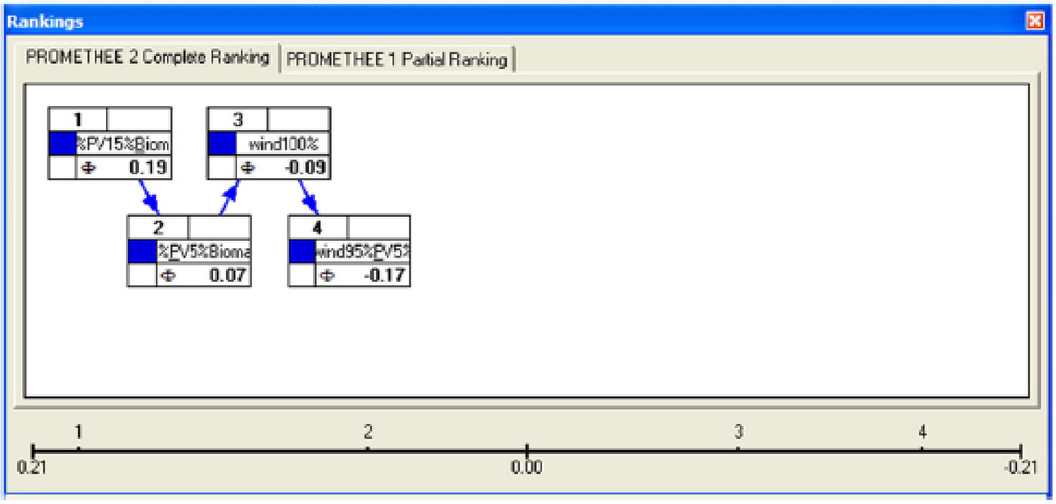

Figure 62 Rankings for the four alternatives from the academic institutions perspective (Tsoutsos *et al.*, 2009)

Appendix 3A: Description of Criteria Used in CCS Decision Analysis Example

A description of the criteria used in the CCS decision analysis example in Chapter 5 is outlined below.

There are 11 criteria associated with CCS implementation that a decision maker is asked to prioritize. The criteria below have units based on what is commonly used in the literature. Most environmentally-focused criteria are stated in relation to a single chemical such as CO_2 equivalents (since many chemicals contribute to each criterion) per unit of energy produced (kWh) with an assumption of 500 MW produced at the CCS plant. Social studies were based upon public opinion surveys. Responses were ranked between 0 and 1 where 1 is a more positive response. Economic criteria are stated on a 'per tonne of CO_2' (TCO_2) basis unless otherwise noted. Engineering criteria have a variety of units.

1. Environmental Criteria

Each of the environmental criteria shown below reflects the percentage change (decrease or increase) in emissions due to adding CCS to a traditional coal power plant. They are shown on a per kWh basis.

1a. Air

1a. 1 Global Warming Potential (GWP) (% reduction in gCO_2-e/kWh):

Although CCS reduces the quantity of CO_2 emitted into the atmosphere, the percentage of CO_2 reduced varies. The variation is largely due to the type of capture technology used and its impact on the efficiency of the power plant, which results in an energy penalty.[14]

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[14] The process of capturing, compressing and transporting CO_2 from a power plant requires a significant amount of energy and is referred to as an energy penalty. Approximately 10-40 % additional energy is required to produce electricity from a power plant as compared with a similar plant without CCS, depending on the conditions and the technology used (IPCC, 2005)

1a.2 Human Toxicity Potential (HTP) (% reduction in years of life lost/kWh):

Human toxicity is mostly a function of flue gas emissions comprising Hydrogen Flouride, NO_x, SO_2, HCl and particulate matter (Koornneef *et al.,* 2008). These chemicals are released from power plants, and their levels are affected by adding CCS to a project.

1b. Water and Land

1b.1 Eutrophication Potential (EP) (% reduction in PO_4^{3-}-e/kWh):

Eutrophication is a function of chemicals such as NO_x, SO_2, NH_3 and PO_4^{3-} and refers to the excessive supply of nutrients to soil and water (Pehnt and Henkel, 2009). NH_3 is the main contributor, caused by the degradation of the Monoethanolamine (MEA) which is currently the most common capture medium used in CCS.

2. Social Criteria

The scales used in surveys tend to be question-specific. The data on each social issue has been condensed into a constructed scale so that multiple studies can be compared. The best possible response was given a value of 1, while the worst response was given a value of 0.

2.1 Public Perception (Constructed Scale 0-1):

Overall opinion of the CCS project by the public.

2.2 Knowledge of CCS (Constructed Scale 0-1):

Awareness and understanding of CCS by the public.

2.3 Perceived Health Impact (Constructed Scale 0-1):

Perception of the positive or negative impact of CCS on human health.

3. Economic Criteria

3.1 Capture Cost (\$/tCO_2 Captured):

Capture cost refers strictly to the capture technology costs for capturing CO_2 and separating the gas from the flue gases. This would be the cost of a CCS project if transportation and storage were excluded.

3.2 Transport Cost (\$/tCO_2 Transported):

Transport cost includes the costs of compressing CO_2 and piping the supercritical fluid to the storage site. The CO_2 is considered to travel a distance of 50 and 100km for the two projects A and B respectively.

3.3 Storage Cost (\$/tCO_2 Stored):

Storage cost includes all aspects of injecting and monitoring CO_2 into a geological reservoir.

4. Engineering Criteria

4.1 Storage Potential (t of Stored CO_2):

The storage potential is the total quantity of pore space available in a geological reservoir for CO_2 storage. This does not take into account other aspects of storage, including the rate at which CO_2 can be injected into the reservoir. The CO_2 capacity is considered to be 30 and 20 million tonnes for project A and B respectively.

4.2 Enhanced Oil Recovery (\$/tCO_2):

When CO_2 is injected into depleted oil and gas reservoirs, it dissolves in the oil resulting in swelling and reduction in viscosity and re-pressurizes the reservoir. This can help produce up to 15% additional oil from oil reservoirs.

Appendix 3B Survey Procedure

The procedure used to conduct the CCS pilot study in Alberta, (and part of the submission for an ethics approval), described in Chapter 6 is outlined below.

- Introduction and explanation of study
    - Explain study and introduce researchers to the participants
- Reading summary sheet
    - Participants reviewed the summary data sheet which served to provide the necessary context to elicit the stakeholders' preferences for the various decision criteria. It is meant to provide information on the criteria as well as give an idea of normal ranges of values for each criterion.
- Reviewing model and assigning preferences to criteria
    - Participants were provided with an Excel sheet with the outlined criteria and summary sheet. Participants were given 100 points to assign to the criteria based on how important they believe each criterion is to the viability of a CCS project. A higher number represents a higher importance.
    - As participants were not experts in fields covering all criteria, we asked that participants then assign a confidence level to their answers for each criterion. This allowed participants to give an estimate of their knowledge about each criteria and their confidence in their scoring. Their confidence scales were multiplied by the scoring to give an overall scoring. The following scale was used:
        - 5 Very confident
        - 4 Confident
        - 3 Moderately confident
        - 2 Slightly confident
        - 1 Very unconfident
- Running simulations of the model
    - Using @Risk and Precision Tree software a Monte Carlo simulation was run on the MCDA model to provide probabilistic results and suggest a preferred CCS option.
- Assessing results of study and allowing for participants to adjust their preferences
    - Participants were able to review their results and make changes if desired.
- Questions and discussion

Appendix 3C Introduction to Study

The email and letter used as an introduction of the study to CCS experts in Alberta is shown below.

Dear Sir/Madam: May 17, 2012

Dalhousie University is building a risk assessment model for Carbon Capture and Storage (CCS). In collaboration with Alberta Innovates Technology Futures (AITF), the data input for the model is being evaluated and adjusted. We are seeking participants that are experts in the CCS field from academia, industry and government to give their opinions about the relative importance of a diverse set of risks for CCS projects. You have been identified as an expert and we are sending you this invitation to participate in the study. Your participation in the study will consist of a 1 to 1.5 hour interview and will help complete the research for a PhD thesis.

Accompanying this letter is provided:

- a summary sheet explaining the project;
- a link to a 13-minute video demonstrating how the project's CCS risk assessment process is applied.

The data included in the summary sheet will be updated as part of the study and will be discussed with you in person as well. A summary of the study's findings will be provided to participants. The final model will be available to all the participants in the project for their use. Please reply to John Choptiany to let us know your availability for the study. John will be interviewing in person in the period between May 31 and June 15. If you decide to participate in the study, John will arrange a time convenient for you and him within that period. If you have any questions you can contact any of us.

Sincerely

John Choptiany BSc, MREM

Interdisciplinary PhD candidate Dalhousie University

John.Choptiany@dal.ca, Jchoptiany@gmail.com

902-440-6741

cc: Dr. James Brydie or Dr. William D. Gunter

Alberta Innovates Technology Futures

James.Brydie@albertainnovates.ca

Bill.Gunter@albertainnovates.ca

cc: Dr. Ronald Pelot

Dalhousie University

Ronald.Pelot@dal.ca

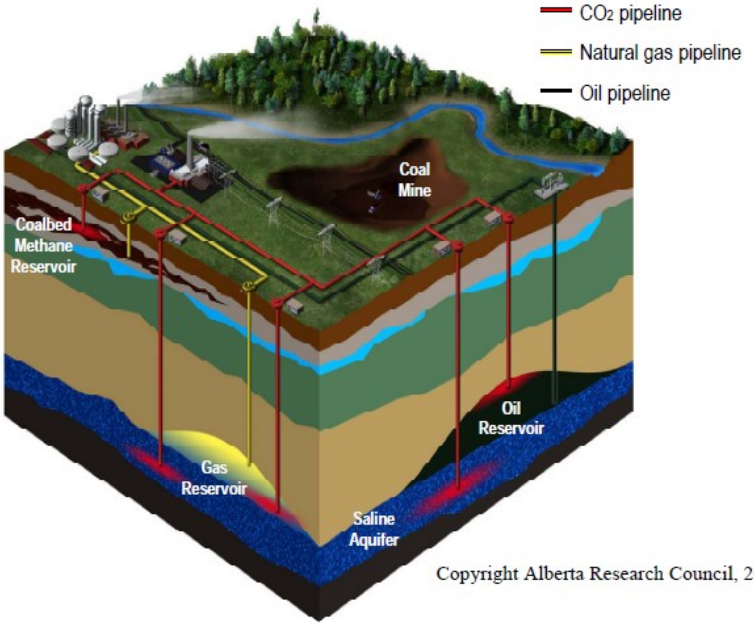
902-494-6113

Appendix 3D Summary Sheet for Participants A Multi-Criteria Decision Analysis and Risk Assessment Framework for CCS: Data Sheet

This appendix is a copy of the summary sheet provided to participants in the CCS case study described in Chapter 6.

John Choptiany, PhD. Candidate, Dalhousie University, Jchoptiany@gmail.com

I hope that you will agree to participate in this research. Your participation as an expert will help in completing a PhD in decision analysis for Carbon Capture and Storage (CCS). In appreciation of your participation, a summary of the findings in the PhD thesis will be provided to participants. The final model will be available to all the participants in the project for their use. Please note that although, the model focuses on CCS, the decision criteria can easily be changed to address subsets of CCS or to compare CCS to competing forms of energy. The uniqueness of the model consists of the integration of a variety of risk analysis tools to aid in decisions around CCS projects. A description of the complete model and its use is available in a presentation on Vimeo which is similar to Youtube. The link is https://vimeo.com/42160434 (CTRL+click to follow the link). The password is simply the three letters, 'CCS' and is case sensitive (if you encounter problems with the Vimeo link, let me know). Figure 63 represents the major components of a CCS project.



Copyright Alberta Research Council, 2005

Figure 63 Schematic of Carbon Capture and Storage (CCS)

This model is being used to assess complex CCS decisions at a high-level. For this example you are acting as a **high-level decision maker in an energy company** faced with choosing between three CCS projects and how best to implement them. The decision to proceed with CCS has already been made. The case studies shown below are based in part on actual CCS projects but have been significantly altered by manipulating data to allow for the projects to be compared on the same scale and by adding literature-sourced data where project-specific information was unavailable.

The study process will involve:

- Reading the data sheet below.
- Assign weights to each criterion based on your opinion of their relative importance to the viability to a CCS project. The total weights assigned to the criteria should add up to 100.
- Assign a value (out of 5) to each criterion on how confident you are on your weighting based on your expertise in that area.

A simulation using the risk/decision model will then be run to see how your weights and preferences influence which project is chosen. Because the model is based on hypothetical, although realistic data, and uses weights assigned by experts, there is no right or wrong decision; only a decision that reflects which aspects of a CCS project you believe to be the most important to the viability of a project.

This sheet is designed to provide information for each of the criteria shown below and to provide context for a 'normal' range of values associated with CCS projects. Data were collected from interviews, peer-reviewed literature, engineering reports and expert opinion. In your assessment, the weighting factors you assign should be independent of the values contained in the table for each criterion. These values are representative values only and are subject to revision. The weighting factors and confidence number is based on your opinion of the importance of each criterion to the decision making process. The last page of this document contains the criteria tables for you to assign your weightings and confidence numbers. You can either complete it now and e-mail me back the tables at jchoptiany@gmail.com or, if you don't have the time, you can complete them during our 90 minute interview in June.

3D.1 OVERVIEW OF CONCEPTS

Carbon capture and storage comprises three separate technologies for capturing, transporting and storing CO_2.

3D.1.1 Capture and Separation of CO_2

Although CO_2 is produced from many diffuse sources, it is only economically feasible to capture CO_2 from large point sources such as gas processing plants, fertilizer manufacturing plants and thermal power plants (IEA, 2004). Current technology captures approximately 85-95% of CO_2 produced in fossil fuel power plants depending on the fuel input and the capture technology. The capturing and separation portion of CCS has been in use for several decades in the natural gas processing industry (IPCC, 2005).

Post-combustion CCS technology is the most developed capture technology and is already in use in several locations worldwide. Post-combustion capture refers to the collection of CO_2 gas from the flue gas after the fuel has been burned to produce electricity. The capturing therefore takes place in the flue gases and is similar to other processes involving ‘scrubbing’ pollutants such as those for SO_x and NO_x.

3D.1.2 Compression and Transport

Typically power plants are not sited based on suitable geological storage for CO_2 and thus the distances between the generation and storage locations are expected to be on the order of tens to hundreds of kilometres. For distances that are up to 1,000 kilometres, and those that involve large quantities of CO_2 transport, pipelines are the preferred and least expensive option.

Transport of CO_2 by pipeline has been occurring for many years and operates in a mature market with over 2,500 km of pipelines in the United States alone (IPCC, 2005). On shorter pipelines an upstream compressor pushes the CO_2, while longer pipelines require periodic compressors to ensure adequate pressure throughout. The technologies, risks and costs associated with transporting CO_2 are not expected to be a barrier to CCS, as they are well known and leaks are very rare.

3D.1.3 Storage

Research has shown that the sites with the most potential for storage occur in depleted oil and gas fields, coal-bed methane reservoirs, deep saline aquifers and salt caverns (Natural Resources Canada, 2006). There may also be significant storage capacity offshore in similar geological formations although this is less well studied and more costly. All these methods involve injecting CO_2 into porous rock formations up to several kilometres below Earth’s surface with an impermeable layer above to prevent the upward migration of CO_2 to the surface.

3D.2 ASSESSMENT CRITERIA

There are 19 criteria associated with CCS implementation that you will be asked to prioritize. The criteria below have units based on what is commonly used in the literature. Most environmentally-focused criteria are stated in relation to a chemical such as CO_2 equivalents (since many chemicals contribute to each criterion) per unit of energy produced (kWh) with an assumption of 500 MW produced at the CCS plant. Social studies were based upon public opinion surveys. Responses were ranked between 0 and 1 where 1 is a more positive response. Economic criteria are stated on a per tonne of CO_2 basis unless otherwise noted. Engineering criteria have a variety of units.

3D.2.1 Environmental

The three main categories of environmental impacts are potential adverse effects to the air, water and land (*i.e.* aquifers, soils and associated ecosystems). Due to a lack of data relating to water and land, air impacts were predominantly used in this assessment. Each of the environmental criteria shown below reflects the percentage change (decrease or increase) in emissions due to adding CCS to a traditional coal power plant. They are shown on /kWh basis.

3D.2.1.1 Global Warming Potential (GWP) (% Reduction in gCO_2-e/kWh):

Although CCS reduces the quantity of CO_2 emitted into the atmosphere, the percentage of CO_2 reduced varies. The variation is largely due to the type of capture technology used and its impact on the efficiency of the power plant which results in an energy penalty.[15]

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[15] The process of capturing, compressing and transporting CO_2 from a power plant requires a significant amount of energy and is referred to as an energy penalty. Approximately 10-40 % additional energy is required to produce electricity from a power plant as compared with a similar plant without CCS, depending on the conditions and the technology used (IPCC, 2005)

3D.2.1.2 Photochemical Ozone Creation Potential (POCP) (% Reduction in gC_2H_4-e/kWh):

Also referred to as 'summer smog', this criterion reflects the creation of near ground ozone through the combination of sunlight, nitrogen and volatile organic compounds (VOCs). VOCs and nitrogen oxides are produced in the combustion of fossil fuels including power plants. POCP negatively impacts breathing and inhibits plant functions. POCP generally increases due to the inclusion of CCS on power plants.

3D.2.1.3 Acidification Potential (AP) (% Reduction in gSO_2-e/kWh):

Acidification is the process of reducing the pH of a substance, in this case through the release of SO_2 emissions from burning fossil fuels (Penht and Henkel, 2009).

3D.2.1.4 Human Toxicity Potential (HTP)(% Reduction in Years of Life Lost/kWh):

Human toxicity is mostly a function of flue gas emissions comprising Hydrogen Flouride, NO_x, SO_2, HCl and particulate matter (Koornneef *et al.,* 2008). These chemicals are released from power plants and are affected by adding CCS to a project.

3D.2.1.5 Eutrophication Potential (EP) (% Reduction in PO_4^{3-}-e/kWh):

Eutrophication is a function of chemicals such as NO_x, SO_2, NH_3 and PO_4^{3-} and refers to the excessive supply of nutrients to soil and water (Pehnt and Henkel, 2009). NH_3 is the main contributor, caused by the degradation of the Monoethanolamine (MEA) which is currently the most common capture medium used in CCS.

3D.2.2 Social

The scales used in surveys tend to be question-specific. The data on each social issue has been condensed into a constructed scale so that multiple studies can be compared. The best possible response was given a value of 1, while the worst response was given a value of 0.

3D.2.2.1 Public Perception (Constructed Scale 0-1):

Overall opinion of the CCS project by the public.

3D.2.2.2 Knowledge of CCS (Constructed Scale 0-1):

Awareness and understanding of CCS by the public.

3D.2.2.3 Perceived Health Impact (Constructed Scale 0-1):

Perception of the positive or negative impact of CCS on human health.

3D.2.2.4 Perceived Impact on Climate Change (Constructed Scale 0-1):

Perceived impact of CCS on climate change relative to other climate change mitigation actions.

3D.2.2.5 Perceived Impact on Other Technologies (Constructed Scale 0-1):

Perceived impact of CCS on the development of other climate change mitigation technologies. One common concern regarding CCS is that pursuing the technology will reduce the effort and funding to more sustainable mitigation actions such as renewable energy projects.

3D.2.3 Economic

3D.2.3.1 Capital Cost ($ in Millions):

This includes all the incremental costs involved in developing the project and constructing all the necessary components of the CCS plant including capture, transport, injection, and monitoring.

3D.2.3.2 Capture Cost ($/tCO$_2$ Captured):

Capture cost refers strictly to the capture technology costs for capturing CO_2 and separating the gas from the flue gases. This would be the cost of a CCS project if transportation and storage were excluded.

3D.2.3.3 Transport Cost ($/tCO$_2$ Transported):

Transport cost includes the costs of compressing CO_2 and piping the supercritical fluid to the storage site. The CO_2 is considered to travel a distance of 50, 100 and 150km for project A, B and reference case respectively.

3D.2.3.4 Storage Cost ($/tCO$_2$ Stored):

Storage cost includes all aspects of injecting and monitoring CO_2 into a geological reservoir.

3D.2.3.5 Overall Operating Cost ($/ Year, in Millions):

As with any construction project, there will be incremental operating costs for CCS. These may be different depending on the type of technology and how dependable CCS components are.

3D.2.3.6 Cost of Electricity ($/kWh):

Cost of electricity is the incremental cost of producing each kWh, including all subsidies and extra costs of CCS relative to a project without CCS.

3D.2.4 Engineering

3D.2.4.1 CO_2 Capture Efficiency (% CO_2 in the Flue Gas Captured):

CO_2 capture efficiency refers to the percentage of the CO_2 gas that is captured from the flue gas. Whatever is not captured is released into the atmosphere. A higher efficiency is thus preferred.

3D.2.4.2 Storage Potential (T of Stored CO_2):

The total quantity of pore space available in a geological reservoir for CO_2 storage. This does not take into account other aspects of storage including what rate CO_2 can be injected into the reservoir. The CO_2 capacity is considered to be 30, 20, and 25 million tonnes for project A, B and reference case respectively.

3D.2.4.3 Enhanced Oil Recovery (\$/tCO_2):

When CO_2 is injected into depleted oil and gas reservoirs, it dissolves in the oil resulting in swelling and reduction in viscosity and re-pressurizes the reservoir. This can help produce up to 15% extra oil from oil reservoirs.

3D.3 CASE STUDIES

This research considers three projects; two based on real case studies and one based strictly on a literature-derived scenario. Basic information about the three case studies can be seen in Table 38. Each project is capturing the CO_2 for 30 years from a 500 MW coal-fired power plant which emits 4 Mt CO_2 annually. At the end of each project, approximately 120 Mt CO_2 will be stored. As most depleted oil and gas reservoirs do not have such large capacities, a number of reservoirs have to be used to store the total CO_2 captured for each case.

3D.3.1 Project A

Project A is based on a hypothetical project in Alberta using a combination of project-specific data and data from peer-reviewed literature.

3D.3.2 Project B

Project B is based in Saskatchewan using a combination of project-specific data and data from peer-reviewed literature.

3D.3.3 Reference Case

A third example is based exclusively on literature and is used to provide a baseline for estimates of CCS projects in general. This project is set in Europe.

Table 38 Case study information

Case study	**Project A**	**Project B**	**Reference case**
Fuel Source	Coal	Coal	Coal
Capture type	Post combustion	Post combustion	Post combustion
Power output (MW)	500	500	500
Transportation distance	100km	150km	50km
Storage type	Depleted oil field	Depleted oil field	Depleted oil field
Storage reservoir capacity	30 million tonnes	20 million tonnes	25 million tonnes
Storage reservoirs needed	4	7	5
Project lifespan	30 years	30 years	30 years
Location	Alberta	Saskatchewan	Europe

3D.4 CRITERIA DATA

In this scenario we are assuming that the decision to develop a CCS project has already been made and the decision makers are comparing the projects on the criteria below.

In the context of the data provided below, please assign weights to the criteria based on your opinion of their relative importance to the overall viability of a CCS project. ***Please distribute 100 points between all criteria.***

Based on your knowledge and confidence in your weighting values for each criterion, please assign a value 1(low) – 5(high) confidence level for each criterion weight assessed.

Return this last page when completed to jchoptiany@gmail.com

3D.4.1 Environmental

	Project				
Criteria	**Project A**	**Project B**	**Reference case**	**Weight**	**Confidence (1-5)**
Global Warming Potential (GWP): % reduction in (gCO_2 e/kWh)	79%	85%	80%		
Photochemical Ozone Creation Potential (POCP): % reduction in (gC_2H_4e/kWh)	10%	15%	20%		
Eutrophication Potential (EP): % reduction in ($gPO_4^{3-}e$/kWh)	25%	25%	15%		
Acidification Potential (AP): % reduction in (gSO_2 e/kWh)	15%	20%	20%		
Human Toxicity Potential (HTP): % reduction in (Years of life lost/kWh)	30%	15%	20%		

3D.4.2 Social

	Project				
Criteria	**Project A**	**Project B**	**Reference case**	**Weight**	**Confidence (1-5)**
Public Perception (0-1) Higher is better	0.223	0.327	0.182		
Knowledge of CCS (0-1) Higher is better	0.307	0.387	0.127		
Perceived Impact on Health (0-1) Higher is better	0.172	0.162	0.142		
Perceived Impact on Climate Change (0-1) Higher is better	0.309	0.267	0.295		
Perceived Impact on Other Technologies (0-1) Higher is better	0.281	0.281	0.281		

3D.4.3 Economic

	Project				
Criteria	**Project A**	**Project B**	**Reference case**	**Weight**	**Confidence (1-5)**
Incremental Capital Cost ($) in millions	1,500	1,650	1,350		
Capture Cost ($/$tCO_2$)	49	54	44		
Transportation Cost ($/$tCO_2$)	1.06	1.33	.78		
Storage Cost ($/$tCO_2$)	2.16	3.42	2.58		
Incremental Operating Cost ($/year) millions	104	115	93		
Incremental Cost of Electricity ($/kWh)	0.0486	0.050	0.0498		

3D.4.4 Engineering

	Project				
Criteria	**Project A**	**Project B**	**Reference case**	**Weight**	**Confidence (1-5)**
CO_2 Capture Efficiency (%)	87	90	85		
Storage Potential/Reservoir (Mill. tCO_2)	30	20	25		
EOR revenue ($/$tCO_2$)	51	45	30		