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Lifecycle risk management for integrated CCS projects

Gestion du risque du cycle de vie des projets CSC intégrés

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

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For an explanation on the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see the following URL: www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 265, *Carbon dioxide capture, transportation, and geological storage*.

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Introduction

Carbon Capture and Storage (CCS) is a process that can mitigate the CO_2 emissions from power plants and other industrial sources of CO_2. CCS draws on many decades of experience in the electricity generation, industrial gas separation, chemical and manufacturing industries, and oil and gas industries, including substantial experience with subsurface injection techniques.

Many of the individual processes (or project phases) that are linked together to comprise a CCS chain have been proven for some time, albeit often in different contexts. Others are still being developed or adapted to this new application. Additionally, bringing them together in a CCS configuration represents a new application, with which there is limited global experience to date. As a result, there is an important need for knowledge development as real experience is gained in the comprehensive application of these technologies.

As with most technologies, CCS has inherent risks which need to be analysed and managed. Integrated projects, given their especially long-term and multi-component aspects, impose particular importance and challenge upon comprehensive risk identification. Risk assessment (detailed risk description and quantification) is completed using all available data, and assessment refreshed with updated numerical simulations which enable comprehensive risk analysis throughout the project lifecycle. The project lifecycle extends across all project phases from business development to site selection through post-closure. Together, risk identification, assessment, analysis, evaluation, management, and treatment are integrated into a risk management plan. The risk management plan aids in decision-making by the owner/operator and, to the extent the results of planning are communicated, aids other stakeholders in evaluating the project.

Keys to the success of the risk management plan are the integration and iterative application of risk assessment, risk data, and risk analysis. Risk analysis and numerical simulation help to identify, estimate and mitigate risks that may arise from CCS projects. These tools are also useful to optimize the design and operation of the monitoring, verification, and accounting aspects of the projects and can serve to inform and facilitate more effective site characterization and model improvement. Importantly, risk tools can be used to shape the design and operation of preventive and remediation options at every stage in the project lifecycle. Effective risk management communication to stakeholders who may be affected is crucial to the success of the project. The risk management plan can serve as a key component of the information handled through the public outreach and communication plan.

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Lifecycle risk management for integrated CCS projects

1 Scope

This document is designed to be an information resource for the potential future development of a standard for overall risk management for CCS projects. The risks associated with any one stage of the CCS process (capture, transportation, or storage) are assumed to be covered by specific standard(s) within ISO/TC 265 and other national and/or international standards. For example, the risks associated with CO_2 transport by pipelines are covered in ISO 27913. The scope of this document is intended to address more broadly applicable lifecycle risk management issues for integrated CCS projects. Specifically, the focus of this document is on risks that affect the overarching CCS project or risks that cut across capture, transportation, and storage affecting multiple stages. It needs to be noted that environmental risks, and risks to health and safety should be very low for CCS projects provided the project is carefully designed and executed. Risk identification and management is part of the due diligence process.

A list of acronyms is included in Annex A.

Clause 5 includes an analysis of how a CCS standard could address aspects of risk analysis that apply to all elements of the CCS chain, such as:

— risk identification (identifying the source of risk, event, and target of impact)[1)];

— risk evaluation and rating;

— risk treatment;

— risk management strategy and reporting.

Clause 6 comprises an inventory of the overarching and crosscutting risks. These include issues such as:

— environmental impact assessment;

— risk communication and public engagement;

— integration risks between capture, storage, and transportation operators, such as risk of non-conformance of CO_2 stream to required specifications;

— integration risks associated with shared infrastructure (hubs of sources, common pipelines, hubs of storage sites);

— risks resulting from interruption or intermittency of CO_2 supply and/or CO_2 in-take;

— risks associated with policy uncertainty;

— incidental risks from activities related to the capture, transportation or storage processes without being specifically covered in the respective standards (e.g. management or disposal of water produced as a by-product of CO_2 storage).

Clause 7 describes implications and considerations for a potential standard on lifecycle risks for integrated CCS projects.

1) As defined in ISO 31000.

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2 Normative references

The following referenced documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 27917, *Carbon dioxide capture, transportation and geological storage — Vocabulary — Crosscutting terms*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 27917 apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

4 General information on lifecycle risk management for CCS

4.1 Usefulness and benefits of lifecycle risk management

Overarching, or crosscutting risk management may help inform future investment and regulatory decisions regarding the risks associated with a CCS project lifecycle. Such evaluations of overarching lifecycle risk already have been performed for previous CCS projects, either as part of an Environmental Impact Assessment [Gorgon (Chevron) and Shengli Dongying (SINOPEC)] or as a requirement of the regulatory or permitting process.

A future International Standard that builds on previous requirements in relevant industries could help future project developers in meeting permitting requirements and help ensure that risks associated with a CCS project are comprehensively identified, evaluated, and managed. In addition, it may promote an appropriate management of risks to health, safety and the environment in areas where regulatory frameworks are less comprehensive, and it may inform future regulatory developments.

4.2 Defining lifecycle for an integrated CCS project

Most of the organizations that have previously published guidelines or standards for CCS risks have focused on the lifecycle of the storage component of a CCS project. Figure 1 to Figure 6 present various lifecycle descriptions from published sources.

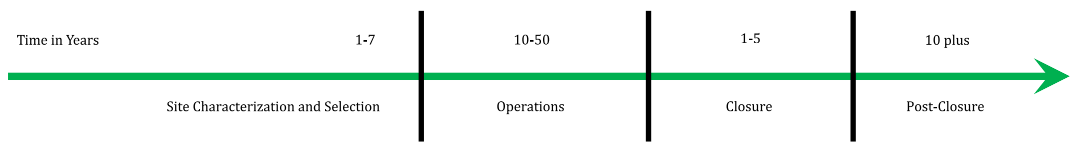

Figure 1 — Timeline for a CCS project defined in the WRI guidelines for carbon dioxide capture, transport, and storage (Forbes et al., 2008)

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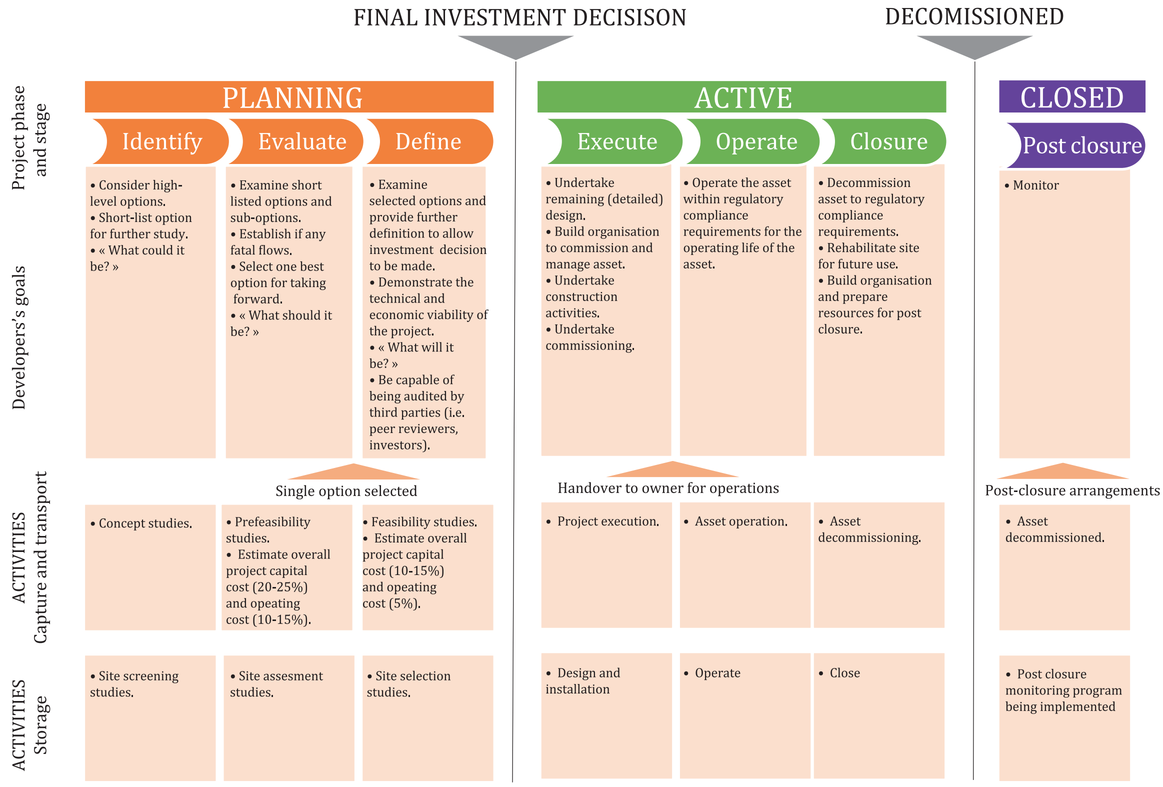

Figure 2 — The project Lifecycle Model of a CCS project developed by the Global CCS Institute (GCCSI, 2015)

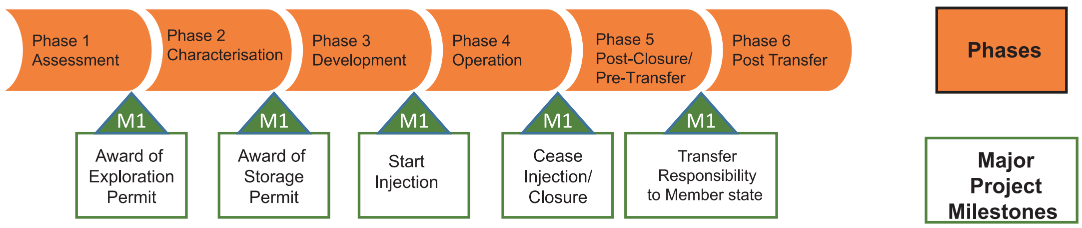

Figure 3 — CO_2 storage lifecycle phases and milestones described in the guidance document of the implementation of Directive 2009/31/EC (European Communities, 2011)[2)]

2) The EU storage project lifecycle definition includes “transfer of responsibility” which might not apply to all jurisdictions.

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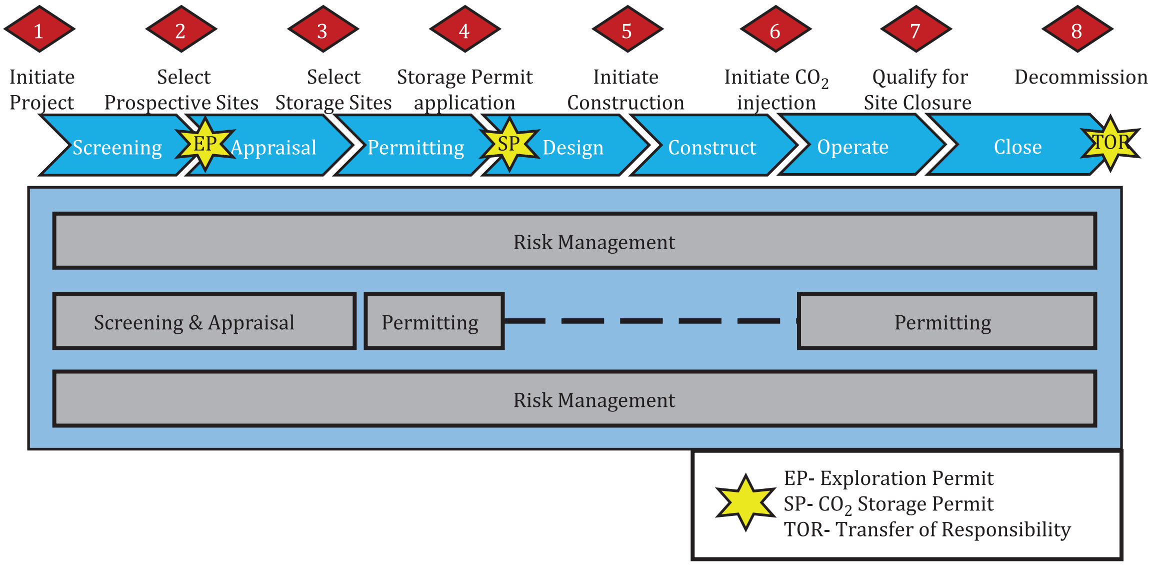

Figure 4 — Carbon dioxide geological storage project lifecycle and associated qualification statements, relevant permits and project milestones defined by DNV (DET NORSKE VERITAS AS, 2012; Det Norske Veritas, 2009)

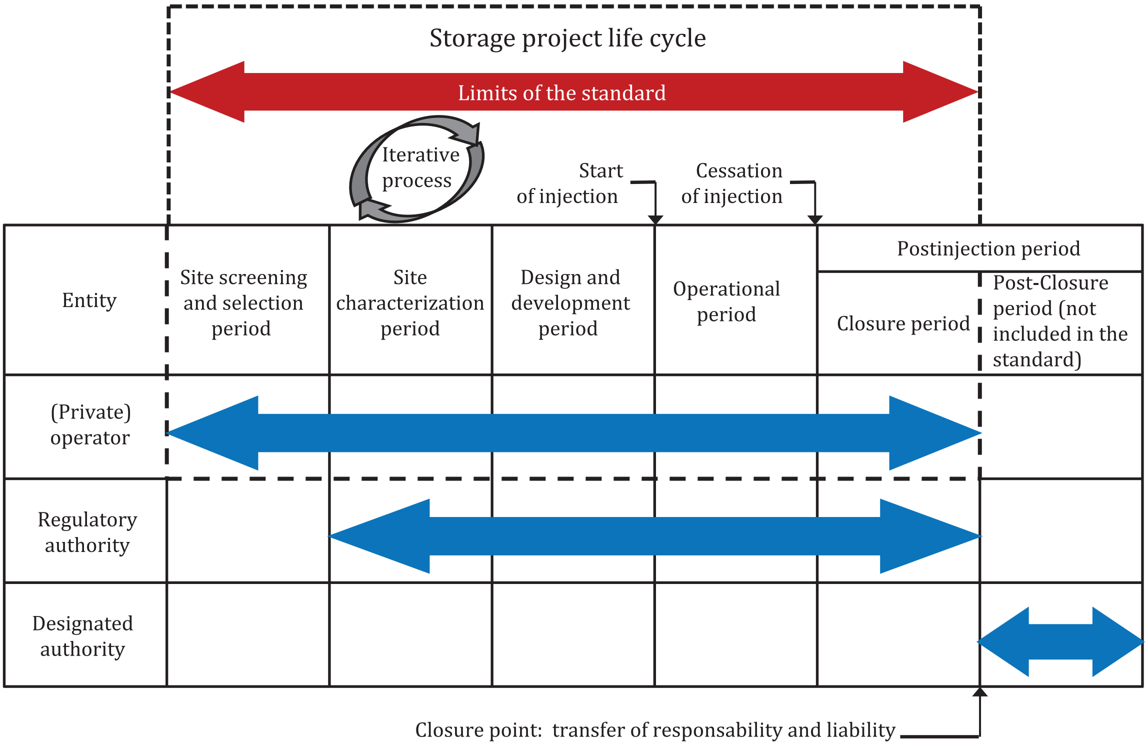

Figure 5 — Lifecycle of a CCS project as defined in Z741 (Canadian Standards Association, 2012)

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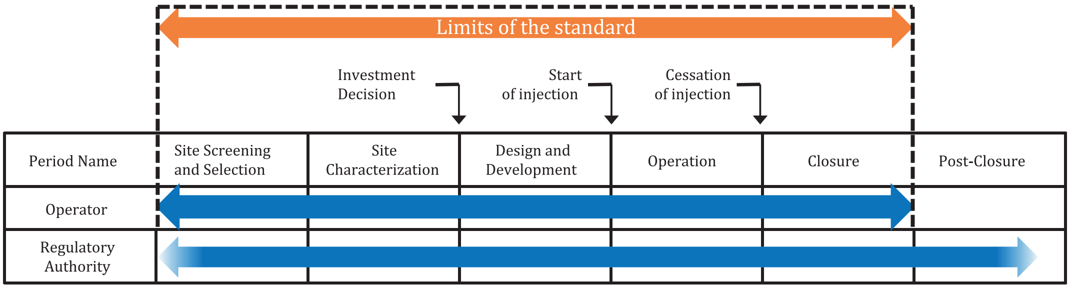

Figure 6 — Lifecycle of a CCS project as defined in in the International Standard for Carbon Dioxide Capture, Transportation, and Storage—Geologic Storage (ISO DIS/27914)

Figure 7 presents the CCS project lifecycle from the point of risk management responsibility and oversight to elucidate the risk source and interaction effect. It was developed based on the Global CCS Institute's (Figure 2) and Canadian Standard Association's (CSA) definitions of lifecycle (Figure 5). As described in Figure 7, the CCS project lifecycle includes all phases of a CCS project from start-up through operation and closure and into the post-closure period. Figure 7 also includes the components of a CCS project, the disposition of the CO_2 stream and the risk management responsibility.

A CCS project lifecycle includes the subsystems (capture, transportation, and storage) as well as temporal elements (project design and initiation, operation, closure, and post-closure). Figure 5 was used in the Canadian Standard's Association's "Z741-12 Geological storage of carbon dioxide" (Canadian Standards Association, 2012) to describe the project lifecycle for a CCS storage project and limitations to the applicability of the standard.

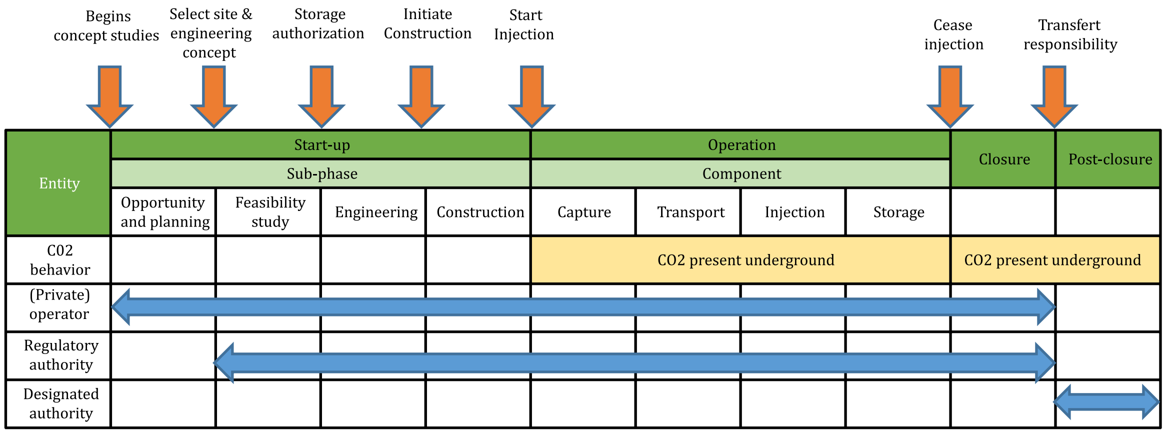

Figure 7 — Proposed CCS project lifecycle from a risk management viewpoint

For the purposes of this document, the lifecycle of a CCS project is defined as having a start-up phase which includes opportunity, planning, engineering and construction; an operational phase which includes capture, transportation and injection; a closure phase; and a post-closure phase. The "decommissioning" stage referenced in Figures 2 and 4 has been omitted because of differences in timing and interpretation across various industries and countries.

4.3 Examples of overarching risk assessment processes conducted for CCS projects

While many tools exist to plan, prepare, and execute risk assessment, analysis, and planning, the following is a brief discussion of the major processes used in the planning and execution (where applicable) of a number of CCS projects. This list includes the risk assessment tools and approaches considered or used by the following projects (operators in parentheses): Weyburn (Cenovus), Gorgon (Chevron), FutureGen 1.0 (FutureGen Alliance), Peterhead (Shell) and White Rose (National Grid Carbon), In Salah (BP), K12-B (GDF Suez), Lacq-Rousse (Total), Snøhvit (Statoil), Otway (CO2CRC),

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PurGen (SCS), Cemex CCS (Cemex), Aquistore (Petroleum Technology Research Centre, or PTRC), and the Regional Carbon Sequestration Partnerships (RCSP, US DOE).

— **Features, Events, and Processes (FEP) database [Quintessa]**: This is an online database tool developed by Quintessa, a scientific and mathematical consulting firm. The database covers technical, operational, and programmatic risks and is used as a qualitative screening tool for health, safety, and environment (HSE), causalities, and environmental (water and air) impacts. Expert input is required both to describe chains of events by which impacts could occur (scenarios) and to describe and quantify the associated risks. This tool has been employed at the Weyburn (Cenovus) and In Salah (BP) projects (Quintessa, 2013).

— **Performance Assessment (PA) Framework for CO_2 [Quintessa]**: In addition to the FEP database, Quintessa has also developed an evidence-based qualitative and quantitative tool which covers technical, operational, and programmatic FEPs. PA allows for the stakeholder assessment of decisions and uncertainty of a project. This tool has been employed at the In Salah (BP) and Quest (Shell) (Quintessa, 2008).

— **Risk Assessment Methodology [TNO]** The TNO methodology covers technical and programmatic risks, focusing on human causality, environmental and groundwater risks. Expert input is required to establish the probability and consequential matrices that can demonstrate long-term safety performance of the underground storage of CO_2 (TNO, 2016). TNO has also developed Carbon Storage Scenario Identification Framework (CASSIF) (Sijacic et al., 2014) which is a qualitative tool requiring expert scenario input to identify storage performance and multiple-site screening.

— **CO_2 QUALSTORE [DNV]**: This product provides guidance on the process and third-party verification for full geologic storage life-cycle risk assessment and analysis as both a qualitative and quantitative tool, using multiple category inputs (VERITAS, 2010). This tool has been used to actively inform discussions between project developers and regulators, including Schwarze Pumpe (Vattenfall) and Quest (Shell). The tool also provided a basis for the DNV-RP-J203 (DET NORSKE VERITAS AS, 2012) certification which has been used for certification by the CarbonNet project (Victorian Department of Economic Development, Jobs, Transport and Resources).

— **URS Risk Identification and Strategy using Quantitative Evaluation (RISQUE**) **[URS]**: This semiquantitative tool focuses on technical and community impacts using key performance indicators. This tool has been employed at Weyburn (Cenovus), Otway (CO2CRC), Gorgon (Chevron), and In Salah (BP) (GCCSI, 2010a) (Dodds et al., 2010).

— **Screening and Ranking Framework (SRF) [Oldenberg]**: This Microsoft Excel based tool uses technical data to allow for expert assessment and assignment of certainties (Oldenberg, 2005). The tool focuses on technical and community HSE aspects and is employed at Ventura oil field and Rio Vista gas field. The definitions of primary containment, secondary containment and attenuation potentially increase data requirements, and the primary and secondary containment are difficult to define for some sites, such as the Ordos basin which has multiple layers. The modified SRF applied to Shenhua CCS pilot project in China discusses these problems, but does not fully overcome them.

— **Vulnerability Evaluation Framework (VEF) [US EPA]**: This qualitative tool addresses HSE, ecosystem, and underground source of drinking water (USDW) impacts to the geosphere utilizing technical input data. The tool can be applied across all aspects of a GS project (US EPA, 2008).

— **Carbon Work Flow [Schlumberger]**: This tool uses expert input to quantify technical and programmatic risks of the project and project goals. The tool requires expert and lay input and is employed at the RCSPs (US DOE), PurGen (SCS), Cemex CCS (Cemex), and Aquistore (PTRC) (US EPA, 2008).

— **Performance and Risk Methodology (P&R) [Oxand and Schlumberger]**: This tool combines qualitative and quantitative risk evaluation in a matrix fashion, focusing on public acceptance, financial, technological, HSE, and USDW impacts(Guen et al., 2009). The tool is employed by the RCSPs (US DOE).

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— **CO_2-PENS [LANL]**: This tool developed by Los Alamos National Laboratory (LANL) uses evidence-based input to consider technical, economic, and community risks. The tool focuses on the full geological sequestration (GS) lifecycle and is employed by the RCSPs (US DOE). It was also used for a risk assessment of the Rock Springs Uplift in Wyoming.

— **MANAUS approach [BRGM]:** BRGM has developed in the framework of the MANAUS project a practical approach for performing a preliminary quantitative risk assessment in an uncertain context. This approach follows the risk assessment principles from the international standards (ISO 31000:2009), which are adapted to account for the specificities and challenges of subsurface operations. In particular the relatively high level of uncertainties expected at early stages of a storage project is accounted for, enabling fully informed decision-making while evaluating risk acceptability (de Lary et al., 2015).

— **CO_2RISKEYE [IRSM-CAS]**: This is an assessment prototype for environmental risk assessment of CO_2 geological storage that is being developed by Li, et al. (Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, IRSM-CAS), which corresponds to the related regulations and guidelines in China. It combines different assessment methods for different purposes, including a modified version of Oldenburg's SRF, Bachu's site-screening method, a fuzzy Analytic Hierarchy Process (AHP) method, and others (Li and Liu, 2016; Liu et al., 2016).

— **National Risk Assessment Partnership (NRAP) [US DOE]:** This performance quantification approach relies on reduced-order models to probe uncertainty in the system. Toolset was built to address key questions about potential impacts related to release of CO_2 or brine from the storage reservoir, and potential ground-motion impacts due to injection of CO_2 (see Table 1). Eight NRAP tools are available for beta testing, e.g. Integrated Assessment Model-Carbon Storage (NRAP-IAM-CS), Natural Seal ROM (NSealR), Reservoir Evaluation and Visualization (REV), Wellbore Leakage Analysis Tool (WLAT), Aquifer Impact Model (AIM), Design for Risk Evaluation and Monitoring (DREAM), Short Term Seismic Forecasting (STSF), and Integrated Assessment Model for Carbon Storage and Reservoir ROM Generation (RROM-Gen). Hypothetical cases have been applied to the tools for demonstration purposes.

Table 1 — Key features of risk assessment tools

Tool	**Application**	**Start-up**				**Operation**			**Closure**	**Post-closure**
		Opportunity	**Planning**	**Engineering**	**Construction**	**Capture**	**Transportation**	**Injection**		
Features, Events, and Processes (FEP) [Quintessa]	Weyburn (Cenovus), In Salah (BP)	x	x	x	x	x	x	x	x	x
Performance Assessment (PA) Framework for CO_2 [Quintessa]	In Salah (BP), Quest (Shell)	x	x	x	x	x	x	x	x	x
Risk Assessment Methodology [TNO]	n/a	x	x					x	x	x
CO_2QUALSTORE [DNV]	Schwarze Pumpe (Vattenfall), Quest (Shell)	x	x	x	x			x	x	x
Risk Identification and Strategy using Quantitative Evaluation (RISQUE) [URS]	Weyburn (Cenovus), Otway (CO2CRC), Gorgon (Chevron), In Salah (BP)	x	x	x	x	x	x	x	x	x

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Table 1 *(continued)*

Tool	Application	Start-up				Operation			Clo sure	Post-clo sure
		Opport unity	Plan ning	Engine ering	Cons truct ion	Cap ture	Tran sport ation	Injec tion		
Screening and Ranking Framework (SRF) and Certification Framework (CF) [Oldenburg]	SRF: Ventura oil field, Rio Vista gas field; modified for Shenhua. CF: In Salah (BP)	x	x	x	x			x	x	x
Vulnerability Evaluation Framework (VEF) [US EPA]	n/a	x	x	x	x			x	x	x
Carbon Work Flow [Schlumberger]	RCSPs (US DOE), PurGen (SCS), Cemex CCS (Cemex), Aquistore (PTRC)	x	x	x	x	x	x	x	x	x
Performance and Risk Methodology (P&R) [Oxand and Schlumberger]	RCSPs (US DOE)	x	x	x	x			x	x	x
CO_2-PENS [LANL]	RCSPs (US DOE), Wyoming Rock Springs Uplift	x	x	x	x	x	x	x	x	x
MANAUS approach [BRGM]	n/a	x	x	x	x			x	x	x
CO_2RISKEYE [IRSM-CAS]	n/a	x	x	x	x			x	x	x
National Risk Assessment Partnership (NRAP) [US DOE]	n/a	x	x	x	x			x	x	x

4.4 Examples of ISO risk standards that may be applied to CCS projects

There is a globally accepted ISO 31000:2018, *Risk management approach — Guidelines*, which may be applied to CCS risk management, including:

— ISO Guide 73:2009, *Risk management — Vocabulary*;

— IEC 31010:2009, *Risk management — Risk assessment techniques*.

Annex of IEC 31010 contains almost all well used risk assessment techniques, including Delphi, fault tree analysis (FTA), event tree analysis (ETA), bowtie diagrams, health risk assessment (HRA), hazard and operability study (HAZOP), and risk matrices.

For CCS specifically, an eventual ISO Standard addressing the CO_2 storage aspects of CCS may include a risk management clause that addresses the following steps:

— establishing the context;

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- risk assessment:
  - risk identification;
  - risk analysis;
  - risk evaluation;
- risk treatment;
- monitoring and review;
- communication and consultations;

4.5 Description of how risk is addressed in other standards and regulations

4.5.1 General

The risks associated with CCS are addressed at the national and international level in agreements and regulations. Previous standards and best-practice guidelines have also addressed risk. However, many of these existing standards and regulations focus exclusively on geological storage of CO_2 and therefore may not adequately address the crosscutting and overarching risks identified and described in this document. 4.5 provides a brief overview of the treatment of CCS risk in international agreements, regional and national regulations, and best-practice manuals.

This subclause focuses on CCS-specific risk assessment provisions which would be applied to integrated CCS projects, however capture and transportation risk assessments are sometimes required for a capture unit or pipeline as a separate measure. For example, in the United States a capture plant would need to comply with the following laws in the Code of Federal Regulations (CFR): 29 CFR §1910.38 (Emergency Action Plans), 29 CFR §1910.119 (Process Hazardous Analysis and Hazardous and Operability Analysis) and 40 CFR Part 68 (Risk Management Plans). These laws ensure that risk management planning is conducted during the design, project management, and construction, pre-start-up and operations life of a facility or part thereof (such as a capture unit).

4.5.2 Treatment of CCS risk in international agreements

4.5.2.1 London Convention and London Protocol

The Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972 (London Convention) and the Protocol of 1996 (London Protocol) have been amended to allow and manage sub-seabed geological storage (Annex 6). The amendments developed and adopted a framework for risk assessment and management of geological storage projects and guidelines for managing geological storage projects. The Annex 6 amendments allow sub-seabed injection of CO_2 when the injected gas or liquid consists “overwhelmingly of CO_2” (it is permissible for it to contain incidental associated substancees derived from the source material, and the capture and sequestration processes used). Additionally, no wastes or other matter are to be added to the CO_2 for the purpose of disposing of those wastes or other matter. In other words, the Protocol’s amendment adopts a non-quantitative standard for the CO_2 content and non-waste quality of the injected CO_2 streams and requires monitoring and controls to maintain that quality. The Annex 6 amendments allowing for sub-seabed storage came into force in February 2007. In 2012, the London Convention adopted “Specific Guidelines for the Assessment of Carbon Dioxide for Disposal into Sub-Seabed Geological Formations (LC34/15, Annex 8) (IMO, 2012). The Guidelines require that the risk assessment describes the risks in terms of the likelihood of exposure and the associated effects on habitats, processes, species communities and uses. The Guidelines also reference mitigation measures, using the risk assessment to inform monitoring programs, and updating the risk assessment at various stages in project to account for short-term and long-term risks. The assessment “should” also take leak mitigation into account.

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4.5.2.2 OSPAR's Guidelines for Risk Assessment and Management of Storage of CO_2 Streams in Geological Formations (Reference Number 2007-12)

Parties to the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR) include the European Union, the 15 governments of the Western European coast, and governments of additional countries located within catchment areas of rivers that flow to the North Sea. OSPAR adopted amendments in 2007 to allow CCS and also adopted guidelines for risk assessment and management. The OSPAR Guidelines incorporate a more detailed Framework for Risk Assessment and Management of storage of CO_2 streams in geological formations (FRAM). These Guidelines have been in force since January 2008. Exact text from the OSPAR Guidelines is included in Box 1 (Dixon, 2007).

The OSPAR Guidelines limit the scope to the injection and storage aspects of a CCS project, with the caveat that capture and transportation should be covered by other national and international regulations. The OSPAR Guidelines cover the full lifecycle of a storage project: planning, construction, operation, site-closure, and post-closure, and emphasize an iterative nature to risk assessment and management throughout this project lifecycle. They provide specific criteria for reporting according to performance criteria at each stage of the project. Stakeholder engagement in the process of risk assessment and management is also required.

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Box 1. The following text is from section VI of the OSPAR Guidelines:

In accordance with paragraph 3 of OSPAR Decision 2007/2:

a) the storage in geological formations of carbon dioxide streams from carbon dioxide capture processes shall not be permitted by Contracting Parties without authorization or regulation by their competent authorities. Any authorization or regulation shall be in accordance with the OSPAR Guidelines for Risk Assessment and Management of Storage of CO_2 Streams in Geological Formations, as updated from time to time. A decision to grant a permit or approval shall only be made if a full risk assessment and management process has been completed to the satisfaction of the competent authority and that the storage will not lead to significant adverse consequences for the marine environment, human health and other legitimate uses of the maritime area;

b) the provisions of the permit or approval shall ensure the avoidance of significant adverse effects on the marine environment, bearing in mind that the ultimate objective is permanent containment of CO_2 streams in geological formations. Any permit or approval issued shall contain at least:

   i) a description of the operation, including injection rates;

   ii) the planned types, amounts and sources of the CO_2 streams, including incidental associated substances, to be stored in the geological formation;

   iii) the location of the injection facility;

   iv) characteristics of the geological formations;

   v) the methods of transportation of the CO_2 stream;

   vi) a risk management plan that includes:

      1) monitoring and reporting requirements;

      2) mitigation and remediation options including the pre-closure phases; and

      3) a requirement for a site closure plan, including a description of post-closure monitoring and mitigation and remediation options; monitoring shall continue until there is confirmation that the probability of any future adverse environmental effects has been reduced to an insignificant level.

c) permits or approvals shall be reviewed at regular intervals, taking into account the results of monitoring programmes and their objectives.

4.5.2.3 United Nations Framework Convention for Climate Change (UNFCCC): Modalities and Procedures for CCS in the Clean Development Mechanism (CDM): FCCC/KP/CMP/2011/10/Add.2

The modalities and procedures for CCS in the CDM were adopted in December 2011 and published in March 2012. A risk and safety assessment is required. As outlined in the modalities and procedures, CDM risk assessment “shall”:

— cover the full chain of CCS (including capture and transportation);

— provide assurance of operational integrity regarding the containment of CO_2 in the geological storage site;

— be used in determining the maximum injection pressure and other operational parameters;

— consider the potential for induced seismicity;

— be used in developing and implementing monitoring activities;

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— provide a basis for remedial measures;

— include a communications plan.

4.5.3 CSA Standard (Z741-12, Geological Storage of Carbon Dioxide)

The CSA Standard served as a seed document for ISO 27914 “Carbon Dioxide Capture, Transportation, and Geological Storage”. The exact text from the CSA standard is provided in Box 2. It is worth noting again that this risk assessment focuses on CO_2 storage, rather than the entire CCS project chain. The CSA standard outlines a risk process that follows the ISO 31000s series, but was written in a CCS-specific context. The CSA standard requires that a robust and technically defensible risk assessment be conducted, and that the results be used to inform the design for the monitoring program. The standard also includes a list of elements to be included in the risk assessment.

Box 2. The following is from section 6.6 in the CSA standard:

Risk assessments shall include a comprehensive risk identification process, technically defensible risk analysis, and a transparent, traceable, and consistent risk evaluation process that aims to avoid bias. The results of the risk assessments shall set performance requirements for risk treatment and be used to inform the design of the monitoring and verification program.

The level of rigor applied to risk assessment shall depend on the available information and the degree of knowledge about risk scenarios required to enable decisions for the relevant stage of the project. In general, the detail in the risk assessment should be gradually enhanced by each pass of the risk management process until the identified risk scenarios are thoroughly assessed.

The project operator shall document in a transparent, traceable, and consistent manner how each of the following elements has been considered in the risk analysis process:

a) description of the risk scenarios;

b) assessment of the likelihood of each risk scenario;

c) assessment of the severity of potential consequences relative to the elements of concern for each risk scenario;

d) identification and description of sources of uncertainty in the likelihood and severity of potential consequences for each risk scenario;

e) identification of measures to reduce or manage uncertainties that can influence the risk evaluation and/or selection of risk treatment;

f) dentification of risk controls to prevent or mitigate identified risk scenarios;

g) description of monitoring targets and detection thresholds required for timely implementation of appropriate risk treatment (identification and selection of appropriate tools that are sufficiently sensitive to detect indicators is part of the design and layout of the monitoring plan);

h) data requirements and modelling and simulation studies to be performed to support the risk analysis (including data requirements and modelling and simulation studies to predict the effectiveness of risk treatment as well as the uncertainty associated with the effectiveness of risk controls);

i) the aggregate likelihood that the respective events could be triggered by one of the identified threats; and

j) the aggregate likelihood that a significant negative impact on each element of concern could follow from one of the respective events.

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4.5.4 US DOE Best Practices for Risk Analysis and Simulation for Geologic Storage of CO_2

The best-practice manual published by the US DOE's National Energy Technology Laboratory (NETL, 2011) outlines best practices for risk analysis and numerical simulation based on the experiences by field projects implemented by the RCSPs. The manual emphasizes the importance of risk assessment in project selection as well as the need to compare measured data to predicted risk assessments and using the assessment together with the data collected to monitor the stored CO_2.

4.5.5 WRI CCS Guidelines

The WRI CCS Guidelines were developed based on a stakeholder process and published in 2008 (Forbes et al., 2008). The exact language from the document is provided in Box 3. Like the CSA Standard, the Guidelines, provide recommendations for risk assessment also focus solely on CO_2 storage, rather than capture, transportation, and storage. The Guidelines differ from the CSA standard in that whereas the CSA standard focuses on identifying risks, the WRI Guidelines highlight a few specific risks that "should" be included as part of the assessment.

Box 3. WRI CCS Guidelines, language on risk assessment.

A risk assessment should be required along with development and implementation of a risk management and risk communication plan for all storage projects. Risk assessments should, at a minimum, examine potential for leakage of injected or displaced fluids via wells, faults, fractures and seismic events, and the fluid's potential impacts to integrity of confining zone and endangerment to human health and environment.

WRI Guidelines offer the following specific guidelines for risk assessment:

a) For all storage projects, a risk assessment should be required, along with the development and implementation of a risk management and risk communication plan. At a minimum, risk assessments should examine the potential for leakage of injected or displaced fluids via wells, faults, fractures and seismic events, and the fluids' potential impacts on the integrity of the confining zone and endangerment to human health and the environment.

b) Risk assessments should address the potential for leakage during operations, as well as over the long term.

c) Risk assessments should help identify priority locations and approaches for enhanced MMV activities.

d) Risk assessments should provide the basis for mitigation or remediation plans for response to unexpected events; such plans should be developed and submitted to the regulator in support of the proposed MMV plan.

e) Risk assessments should inform operational decisions, including setting an appropriate injection pressure that will not compromise the integrity of the confining zone.

f) Periodic updates to the risk assessment should be conducted throughout the project lifecycle based on updated MMV data and revised models and simulations, as well as knowledge gained from ongoing research and operation of other storage sites.

g) Risk assessments should encompass the potential for leakage of injected or displaced fluids via wells, faults, fractures, and seismic events, with a focus on potential impacts on the integrity of the confining zone and endangerment to human health and the environment.

h) Risk assessments should include site-specific information, such as the terrain, potential receptors, proximity of USDWs, faults, and the potential for unidentified borehole locations within the project footprint.

i) Risk assessments should include non-spatial elements or non-geologic factors (such as population, land use, or critical habitat) that should be considered in evaluating a specific site.

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4.5.6 IEA Carbon Capture and Storage Model Regulatory Framework

The IEA's Model Regulations for CCS (2010) include risk assessment as a primary component of site selection as well as an integral part of an Environmental Impact Analysis (EIA). Although the text focuses on the subsurface element, it was written with a clear goal of facilitating integrated projects. The text for risk assessment used in the IEA's model rule specifically notes that it builds on several guidelines and rules for risk assessment that came out of the amendments to the London Protocol and OSPAR. The IEA model framework offers the following recommendations for a CCS risk assessment:

— hazard characterization;

— scenarios and sensitivities;

— consequence analysis;

— risk management.

Like the other frameworks, the IEA model emphasizes the importance of using the risk assessment to define project design, operational and monitoring parameters, and closure and post-closure procedures.

4.5.7 United States EPA regulations

Language used by the United States Environmental Protection Agency's (EPA) in promulgating regulations for permitting Class VI wells for the underground storage of CO_2 is provided in Box 4. As with many of the other examples, the focus is solely on the CO_2 storage aspects of CCS projects. Although risk analysis and management are integral to identifying the monitoring area and designing an emergency response plan, specific guidelines for risk analysis and management are not included in the regulation.

Box 4. US. EPA Regulations for Class VI Geologic Sequestration Injection Wells

Risk analysis and contingency are addressed in two plans required in the permit application: the "proposed area of review and corrective action plan" and the "proposed emergency and remedial response plan." (40 C.F.R. § 146.82)

In the first, "(b) The owner or operator of a Class VI well must prepare, maintain, and comply with a plan to delineate the area of review for a proposed geologic sequestration project, periodically revaluate the delineation, and perform corrective action [on faulty wells] that meets the requirements of this section and is acceptable to the Director." (§ 146.84). As part of this requirement, the owner or operator must "(1) Predict, using existing site characterization, monitoring and operational data, and computational modelling, the projected lateral and vertical migration of the carbon dioxide plume and formation fluids in the subsurface from the commencement of injection activities until the plume movement ceases, until pressure differentials sufficient to cause the movement of injected fluids or formation fluids into a USDW are no longer present, or until the end of a fixed time period as determined by the Director." (§ 146.84)

In the second, "the owner or operator must provide the Director with an emergency and remedial response plan that describes actions the owner or operator must take to address movement of the injection or formation fluids that may cause an endangerment to a USDW during construction, operation, and post injection site care periods." (§ 146.94).

The EPA states that it "agrees ... that the emergency and remedial response plan should be site-specific and 'risk-based.' EPA expects that each emergency and remedial response plan will be tailored to the site, and today's rule provides flexibility to the owner or operator to design a site-specific plan that meets the requirements of § 146.94(a). Rather than requiring specific information in the emergency and remedial response plan that may not be relevant to all GS projects, the plan allows such information to be determined on a site-specific basis." (Federal Register; pg. 77272; Vol. 75, No. 237; December 10, 2010). However, the regulations do not explicitly require the plan to be risk-based.

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4.5.8 EU Directive 2009/31/EC on the geological storage of carbon dioxide

The EU Directive (2009) for geological storage addresses risk assessment as a separate step in the characterization process. Other risks would be addressed through the Environmental Impact Assessment (EIA) Directive. As shown in Box 5, the EU Directive for Geological Storage includes a description of key criteria that “must” be included in the risk assessment. This approach is similar to the WRI CCS Guidelines, but differs from the other regulations which are less specific, or focus more on the risk assessment process. Member states have taken differing approaches in transposing the EU Directive in national regulations, with some adopting new specific legislation for the geological storage of CO_2 and others amending existing laws (European Commission, 2014). The European Commission also issued guidance documents, including the “CO_2 Storage Lifecycle Risk Management Framework” (European Communities, 2011).

Box 5. EU CCS Directive

Step 3 of the characterization and assessment process for potential storage complexes requires “Characterisation of the storage dynamic behaviour, sensitivity characterisation, [and] risk assessment.” (Annex I)

“The risk assessment shall comprise, inter alia, the following

3.3.1. Hazard characterization

Hazard characterization shall be undertaken by characterizing the potential for leakage from the storage complex, as established through dynamic modelling and security characterization described above. This shall include consideration of, *inter alia*:

a) potential leakage pathways;

b) potential magnitude of leakage events for identified leakage pathways (flux rates);

c) critical parameters affecting potential leakage [for example maximum reservoir pressure, maximum injection rate, temperature, sensitivity to various assumptions in the static geological Earth model(s)];

d) secondary effects of storage of CO_2, including displaced formation fluids and new substances created by the storing of CO_2;

e) any other factors which could pose a hazard to human health or the environment (for example physical structures associated with the project).

The hazard characterization shall cover the full range of potential operating conditions to test the security of the storage complex.

3.3.2. Exposure assessment — based on the characteristics of the environment and the distribution and activities of the human population above the storage complex, and the potential behaviour and fate of leaking CO_2 from potential pathways identified under Step 3.3.1.

3.3.3. Effects assessment — based on the sensitivity of particular species, communities or habitats linked to potential leakage events identified under Step 3.3.

3.3.4. Risk characterization — this shall comprise an assessment of the safety and integrity of the site in the short and long term, including an assessment of the risk of leakage under the proposed conditions of use, and of the worst-case environment and health impacts. The risk characterization shall be conducted based on the hazard, exposure and effects assessment. It shall include an assessment of the sources of uncertainty identified during the steps of characterization and assessment of storage site and when feasible, a description of the possibilities to reduce uncertainty.”

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4.5.9 Regulation of geological storage in Japan

In Japan, two legislative schemes handle overarching risks in geological storage of carbon dioxide procedures and operations.

The Ministry of Environment (MOE) rules requirements for sub-seabed carbon dioxide storage projects (Ministry of Environment, 2007). The MOE has the responsibility to approve a specific CO_2 sub-seabed storage project when pre-assessment adequately states that only minor influences and changes happen within the target sea area in the case of CO_2 leakage. Additionally, a project is required to have a monitoring plan for adequate leakage detection and a recovery plan for minimizing the influence on marine environments if any CO_2 leaks. The rules also include an ordinance governing the purity of the injected CO_2. When CO_2 is captured with amine-based technology, CO_2 purity should be no less than 99 % in volume percentage. When the CO_2 is produced out of hydrogen production process for an oil refinery, the CO_2 purity should be no less than 98 % in volume percentage. The law requires that there be an agreed monitoring program. Permission for CO_2 injection sub-seabed is limited for no longer than five years, after which the permit is re-evaluated for renewal.

The Ministry of Economy, Trade and Industry (METI) issued another scheme named "Safety Guideline for Large Scale Demonstration Geological CCS Project" (Ministry of Economy, 2009). It has been adopted for the Tomakomai large-scale CCS project (injection started on 6 April, 2016). The guideline recommends the assessment of overarching risks in stages the planning stages for capture, transportation, injection and also for the post closure period. It also requests the development of scenarios of accidental events and preparation for any emergencies.

4.5.10 Technical guidelines for CCS in China

CCS environmental risk assessment technical guidelines were developed by the Ministry of Environmental Protection (MEP, 2015) of China. The MEP guidelines define the utilization and storage area under review as 'that area surrounding the project which may be threatened by the injection activity'. The time scale defined includes the pre-injection, injection, closure, and post-closure periods. A risk matrix is recommended in this guideline, and the risk level is divided into three categories (low, moderate and high), based on the impact level of receptors and the possibility/likelihood of the risk happening. A more detailed description of the MEP Guidelines is shown in Box 6.

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Box 6. CCS Environmental Risk Assessment Technical Guidelines of MEP, China

2 CCS environmental risk assessment procedures

2.1 Assessment process

CCS environmental risk assessment process includes:

I. Systematic identification of potential sources and critical receptors of environmental risk.

II. Determination of the environmental risk assessment methods and definition of the impact and possibilities.

III. Assessment of the impact and likelihood and estimation of the environmental risk level of each risk source and receptor.

IV. Identification of the environmental risk management systems to reduce the environmental risk to an acceptable level.

2.2 Assessment range

For the capture element, the assessment range is that range inside and outside of the plant which contains the CO_2 source.

For the transportation element, the assessment range is the pipeline, trailer, railway tank and ship and the above-ground and underground volumes around them that might be affected by a CO_2 release.

For the geological storage element, the area of review is that area of the project that may be threatened by the injection activity.

2.3 Time scale of assessment

For the capture element, the timescale of the assessment includes the full operational period of the capture equipment.

For transportation element, the time scale of assessment is the construction and operation period of pipeline, and the operation period of tank car, railway and ship.

For geological storage element, the time scale of assessment is the pre-injection, injection, closure, and post-closure period.

4.5.11 Summary of key features of CCS risk assessment requirements

The best practices and regulations regarding risk assessment for CCS projects which have been adopted to date are very similar. The requirements generally are designed to ensure that a risk assessment be conducted and used during the early design phase of a CCS project and be integrated with the environmental impact assessment and monitoring plan development. The requirements are designed to also ensure that the risk assessment includes contingency or mitigation measures. As a project enters the operational stages, the risk assessment is typically required to be updated with project-specific data. The risk assessment is then revisited during the closure phase and can be used to determine that containment is secure and the project can enter the post-closure phase[3]. Of the frameworks reviewed, only a few encompass the lifecycle of an integrated CCS project and include capture, transportation, and storage; however, some of the storage-focused resources have inherently assumed integrated projects and consequently touch on the associated lifecycle risks. The relevant requirements are summarized in Table 2.

3) A post-closure phase might not exist in all jurisdictions.

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Table 2 — Key features of risk assessment requirements

Organization	Scope (Capture, Transportation, Storage)	Lifecycle or Stage of Project Risk Assessment is Applied
London Convention and London Protocol	Sub seabed storage	Pre-injection, injection, closure, and post-closure
OSPAR Guidelines for Risk Assessment	Storage of CO_2 in geologic formations	Planning, construction, operation, site-closure, and post-closure
UNFCCC Modalities and Procedures for CCS in the CDM	Capture, transportation, and storage	Planning, operation
CSA Standards	CO_2 storage	Planning, construction
NETL Best Practice Guideline	CO_2 storage	Planning, construction, operations
WRI CCS Guidelines	CO_2 storage	Planning, operation, site-closure, and post-closure
IEA Model Rule	CO_2 storage	Planning, construction, operation, site-closure, and post-closure
US EPA	CO_2 storage	Permitting, well construction, operation, well plugging, post injection site care, and site closure
EU Directive	CO_2 storage	Risk assessment for planning, site characterization, and lifecycle risk management.
Japan	CO_2 storage (Marine Pollution Prevention Law) and capture, transportation and injection (Safety Guideline for Large Scale Demonstration Geological CCS Project)	Planning, operations, post-closure
MEP, China	Capture, Transportation and CO_2 storage	Capture — construction, operation; Transportation — construction and operation of pipeline, and operation of tank car and ship Storage — pre-injection, injection, closure, and post-closure

5 Overarching and crosscutting aspects of risk management in CCS projects

5.1 Introduction

5.1.1 Scope

Rather than redefine terms, 5.1 is intended to explain relationships among various risk terms and among various project aspects as they relate to risk management.

5.1.2 Terms relating to risk

Risk is defined by ISO 31000 as "the effect of uncertainty upon persons, upon things valued by persons, or upon future states of being that are desired by persons or by groups of people". For an engineered project, risk is typically assessed (quantified and/or qualified) based on the estimated magnitude of potential negative impact to one or more project performance metrics, multiplied by the estimated probability that the negative impact(s) occurs. The elements of concern may include HSE, cost, or reputation. Performance metrics always include both outcomes that the project strives to achieve, and outcomes that the project strives to avoid such as worker injury and environmental impact. Strictly speaking, the *risk elements* that can be assessed in that way ("impact multiplied by probability" or "severity times likelihood") are defined as specific chains of events, called *scenarios*. Scenarios can be built from features, events, and processes (FEPs.)

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Once assessed, identified project risks can be compared with one another and with the levels of *tolerable risk* as defined by the project's stakeholders, such as operators, financial backers and insurers, and regulatory authorities. This step is termed *risk evaluation,* and it provides the basis and justification for implementing *risk treatments* (actions to reduce risk) and *risk controls* (actions to prevent risk escalation). *Risk management* is the subset of project management that embraces all the foregoing steps; that tracks the effectiveness of the defined treatments and controls; and that supports the project operators' ongoing awareness of risk levels and emergent risks.

5.1.3 Project components and phases

Although CCS projects are conceived as an integrated whole, they are designed and built as components that are largely separate in terms of physical space, technical disciplines, and industrial practice. Consequently, risks have traditionally been identified separately within the components of CO_2 capture, transportation, and geologic injection for storage. In a time sense, projects are subdivided according to phases such as opportunity, planning, engineering and construction, an operational phase which includes capture, transportation, and injection, a closure phase, and a post-closure phase.

However, risk management that focuses solely on isolated project components or phases may fail to identify some risks that relate to the project as a whole, or pertain to the linkages between elements. Solutions that are designed for an isolated risk may not serve the whole project well. Therefore, it is crucial that risk management also include crosscutting and overarching aspects. It is important to identify, evaluate, and treat risk elements beyond those that are tied to isolated project elements.

5.1.4 Responsibilities and risk ownership

Conducting risk assessment and risk management demands thoroughness in both risk identification and risk treatment. Risk scenarios are identified and evaluated within the boundaries and transitions between project components or phases just as much as within the separate project elements. The crosscutting and overarching risks are managed the same as the element-specific risks: if evaluation reveals that a management action is needed, then it is executed and its effectiveness tracked. However, while responsibility for treating and tracking risks may be relatively clear for component-specific risks (the project manager for that component is typically defined as the "risk owner"), the ownership of crosscutting or overarching risks may need clarification. If responsibility for risk treatments is not clearly assigned, risks that affect multiple project components or phases could be overlooked.

The operator(s) typically assume responsibility for treating all overarching risks, as well as any (e.g. crosscutting) risks where responsibility has not been delegated among the managers or technicians who are responsible for project sub-elements (capture, transportation, or storage). Key roles for an overarching project risk manager reporting to the operator can include harmonizing various risk treatments to best support project goals, and clarifying the ownership of responsibility for executing risk treatments.

5.2 Risk identification

5.2.1 General

Risk identification is a part of risk management procedure. Once the context of a risk analysis has been defined, the next step is risk identification. This is a process intended to identify the possible sources, causes, and consequences of risks that could affect the achievement of the project objectives. Risk identification is a critical step in risk management because if a risk is not identified, it will not be managed.

IEC 31010 lists 31 typical risk analysis techniques. Among them, it recommends 15 techniques as strongly applicable for risk identification: brainstorming, Delphi, Preliminary Hazard Analysis (PHA), Hazard and Operability Studies (HAZOP), etc. The document also delineated 11 risk tools as applicable for risk identification: Fault Tree Analysis (FTA), Event Tree Analysis (ETA), Cost/Benefit Analysis, etc.

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A critical attribute of an identified risk is the degree of detail with which it is described. The degree of detail affects the magnitude of risk and how it is compared with other identified risks, which may be described in other degrees of detail.

5.2.2 Identifying overarching and crosscutting (OA-XC) risks

CCS specialists with diverse expertise from countries in North America, Asia, Australia, and Europe and have used group creativity techniques and simplified Preliminary Hazard Analysis (PHA) approaches to identify the overarching and crosscutting risks that would not be handled in the ISO/TC 265 process. The team attempted to comprehensively identify overarching-crosscutting risks and to examine whether their uncertainties would impact CO_2 capture, transportation, and/or storage, and where in the temporal CCS project lifecycle these risks were likely to arise. Overarching (OA), or overall risks are risks that affect the entire CCS project. While crosscutting (XC) risks are risks that affect more than one part of a CCS project chain. The results of this exercise are presented in Table 3. The table categorizes overarching and crosscutting risks into four groups: policy, economic, technical, and HSE-related issues. Additionally, the table shows those sub-systems potentially impacted and the stages of CCS operation. Clause 6 of this document includes a sub-clause on each of the identified OA and XC risks.

Table 3 — Identified overarching (OA) and crosscutting (XC) risks to be addressed in this document

Sub Clause	OA or XC	Policy, Econom-ic, or Techni-cal,	Risk	Whole project (W), or Capture, Trans-porta-tion, or Storage	Start-up				Operation			Clo-sure	Post-Clo-sure
					Op-por-tuni-ty	Plan-ning	Engi-neer-ing	Con-struc-tion	Cap-ture	Trans-por-tation	In-jec-tion		
6.3.2	OA	Policy	Legal Un-certainties (including pore space ownership)	W	X	X	X	X	X	X	X	X	X
6.3.3	OA	Policy	Uncertain cost or reg-ulations for integrated project, e.g. plugging and abandon-ment (clo-sure or post closure)	W	X	X	X	X	X	X	X	X	
6.3.4	OA	Policy	Public engagement (public op-position, risk communica-tion, public disclosure of data, etc.)	W	X	X	X	X	X	X	X	X	X
6.3.5	OA	Policy	Project permits not obtained	W	X	X	X	X	X	X	X	X	X

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Table 3 *(continued)*

Sub Clause	OA or XC	Policy, Econom-ic, or Techni-cal,	Risk	Whole project (W), or Capture, Trans-porta-tion, or Storage	Start-up				Operation			Clo-sure	Post-Clo-sure
					Op-por-tuni-ty	Plan-ning	Engi-neer-ing	Con-struc-tion	Cap-ture	Trans-por-tation	In-jec-tion		
6.3.6	OA	Economic	Lack of financial driver e.g. CO_2 price or credit benefit (oil or other products)	W	X	X	X	X	X	X	X		
6.3.7	OA	Economic	Insufficient project financial re-sources-cost of capital	W	X	X							
6.3.8	OA	Economic	Unexpected construction or opera-tional cost changes	S			X	X	X	X	X	X	
6.3.9	OA	Economic	Uncertain-ty in CO_2 supply	W					X	X	X		
6.3.10	OA	Economic, Policy	Lack of emissions accounting	W		X	X	X	X	X	X		
6.3.11	OA	Technical	Technology scale-up	W			X	X	X	X	X		
6.3.12	OA	Technical	Lack of knowledge or qualified resources for operating the unit	W	X	X	X	X	X	X	X		X
6.3.13	OA	Technical	Project impacts on environment	W				X	X	X	X	X	X
6.3.14	OA	Technical	External nat-ural impacts on project	W					X	X	X	X	X
6.3.15	OA	Technical	External man-made impacts on project	W					X	X	X	X	X
6.3.16	OA	Technical	Site uncer-tainty-plan-ning, conflict with other usage, rights	W				X	X	X	X	x	x

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Table 3 *(continued)*

Sub Clause	OA or XC	Policy, Economic, or Technical,	Risk	Whole project (W), or Capture, Transportation, or Storage	Start-up				Operation			Closure	Post-Closure
					Opportunity	Planning	Engineering	Construction	Capture	Transportation	Injection		
6.4.2	XC	Technical	Accidental or intentional interruption or intermittency of CO_2 supply, CO_2 in-take or transportation	C⇆T⇄S[a]					X	X	X		
6.4.3	OA or XC	Technical	Shared infrastructure by multiple projects (uncertain ownership, performance or lack of co-ordination)	C⇆T⇄S[a]					X	X	X		
6.4.4	OA or XC	Technical	Using existing facilities (especially pipeline, knowledge on condition, obligation to other user, CO_2 or material specifications, uncertain timing)	C⇆T⇄S[a]		X	X	X		X	X		
6.4.5	XC	Technical	Unintended phase change	C⇆T⇄S[a]							X		
6.4.6	XC	Technical	CO_2 out of specifications: source gas composition is not as expected	C→T→S[a]					X	X	X		
6.4.7	XC	Technical	Mismatched component performance (capacity, resource, flexibility, efficiency well integrity or lifetime)	C⇆T⇄S[a]		X	X		X	X	X		

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Table 3 *(continued)*

Sub Clause	OA or XC	Policy, Economic, or Technical,	Risk	Whole project (W), or Capture, Transportation, or Storage	Start-up				Operation			Closure	Post-Closure
					Opportunity	Planning	Engineering	Construction	Capture	Transportation	Injection		
6.4.8	XC	Technical	Lower capture efficiency due to the upstream plant flexible operation	C→T→S[a]		X	X		X				
6.4.9	XC	Technical	Insufficient storage resource	S→T→C[a]							X		
6.4.10	XC	Technical	Reservoir does not perform as predicted (injectivity reduction, storage resource, geomechanical stability, containment)	S→T→C[a]							X	X	X
6.4.11	XC	Technical	Model uncertainties regarding the storage performance (capacity, injectivity, containment)	S→T→C[a]	X	X	X	X			X		X
6.4.12	XC	Technical	Lack of Maintenance and emergency control procedures; Safety related accidents	C⇆T⇄S[a]	X	X	X		X	X	X		
6.4.13	XC	Technical	Corrosion and material problems	C⇆T⇄S[a]					X	X	X		
6.4.14	OA or XC	All	Transportation Risks	T→S→C[a]						X			

[a] The arrows in the table indicate the way in which a risk on one part of a CCS project chain impacts the others.

Based on this exercise, the following recommendations apply to identifying overarching and crosscutting (OA-XC) risks.

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A number of common practices are recommended for identifying overarching and crosscutting risks:

a) Use a team with a range of experience and diverse expertise which covers all CCS subsystems including capture, transportation, and storage;

b) Conduct a systematic approach in sufficient detail to comply with the established objectives and scope of the risk analysis.

c) Apply available and practical techniques for risk identification. Whatever technique is adopted for risk identification, Table 3 can be used as the basis for a checklist to identify overarching and/or crosscutting risks.

d) Ensure that all information that relates to risk targets, sources, and pathways is taken into account: historical data, theoretical analysis, informed opinions, expert advice, and stakeholder input.

e) Perform the first stage of risk identification, for example a Preliminary Hazard Analysis (PHA) could be applied.

5.3 Rating and evaluating risk

5.3.1 Risk assessment, risk tolerance, and risk evaluation processes

For crosscutting or overarching risks, the basic elements of rating and evaluating risk are the same as for component-specific or phase-specific risks. In order to be managed, the risks associated with any scenarios or FEPs relevant to a project need to be assessed and described in a comparable way so that their relative importance can be judged. Risks are *semi*-quantified as the product of categorically scaled attributes that are labelled similarly to

a) impact severity, and

b) likelihood.

The scales for these attributes typically consist of 4 to 10 stepped (ordinal) categories, and each category description uses criteria that can be observed or estimated for the project. Accordingly, assessing a risk according to each scale yields a value between (for example) 4 and 10. The product of those two values generates a *risk magnitude* that – although it is not measurable in an objective sense – can be used to compare risks with different characteristics on a similar basis and to prioritize them.

Once risks are assessed in this way, they can be evaluated with respect to risk tolerance criteria. Risk tolerance criteria may be established methodically by the project operator in consultation with regulators and, potentially, other parties. The evaluation step provides the objective criterion by which the operator judges the need to treat actively (take action to reduce or control) the risk, as compared to merely monitoring it. In concept, the decision scale that is linked to the tolerance criterion has values similar to these:

— Highest risks: “Stop activity immediately until this risk is reduced”.

— Intermediate-level risks: “Proceed with caution and act to reduce this risk as quickly as possible”.

— Lowest risks: “Do nothing now, but maintain watch in case risk increases”.

5.3.2 Risk scales and expert judgment

In the context of crosscutting or overarching risks, the scales of likelihood and severity are developed and expressed. The scales and the risk tolerance standard are defined so as to be applicable to all project components and phases, so that risk control efforts can be applied efficiently and where most needed across the project. The risk scales do not differ among the various project components, but are themselves, crosscutting and overarching.

In order to address crosscutting and overarching risks outside of individual components of a project, the risk manager involves appropriate expertise from the relevant disciplines.

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5.3.3 Risk evaluation for overarching or crosscutting risks

The foregoing (see 5.3.1 and 5.3.2) emphasizes that the presence of overarching and/or crosscutting risks heightens the need for the processes and yardsticks of risk assessment to be consistent across all project components. Two best-practice conclusions emerge from this observation:

a) The risk management process may benefit from including on project staff a specific person whose principal role is project risk manager. This individual is responsible for managing risks (establish and carrying out processes to identify, assess, evaluate, treat, and track risks) across all project components and phases, and advises and reports to the project executive level.

b) Near the beginning of a project, senior project staff and the project risk manager convene to develop and establish the project risk scales and risk tolerance criteria, and to agree on general processes and resource allocation for risk treatment and tracking.

5.4 Risk treatments

5.4.1 General

Risk treatment involves selecting and implementing options to modify risks. Following are typical options for risk treatment:

a) Acceptance (applicable to low risks), i.e. deciding to do nothing to reduce the risk or to control it.

b) Reduction (applicable to high risks), i.e. acting to reduce the likelihood and/or the consequence of the potential mishap (by changing designs, procedures, management methods etc.).

c) Transfer (applicable to risks with serious consequences and low likelihood) by such means as insurance or contractual arrangements.

d) On-going management (applicable to risks with serious consequences and a low likelihood, which could increase unless actively managed).

e) Avoid the risk (applicable to risks with serious consequences and a high likelihood), i.e. not to start or continue with the activity that gives rise to the risk.

f) Retain the risk (applicable to residual risks, left after risk reduction, which may require financing).

The full value of comprehensive risk assessment becomes evident in selecting the most appropriate risk treatment options.

5.4.2 Aspects of risk treatment that are overarching and/or crosscutting

With regard to risk treatments that are overarching-crosscutting in a whole CCS project or part of a CCS project, the process for decision for options and actions to be taken can be conducted on an inter-sub-system basis. Experts from capture, transportation, and storage could be convened to discuss and agree upon risk treatment for overarching or crosscutting issues. The organization can establish internal communication and reporting mechanisms in order to support the risk treatment decision and action. For smooth and effective risk treatment decisions, it is essential to ensure cross-sectional communications and to establish cooperative climate between subprojects. This also encourages the accountability and ownership of risk.

6 Inventory of overarching and crosscutting risks

6.1 General

This clause suggests an approach for addressing overarching and crosscutting risks that have the potential to be significant, as identified in Table 3. It focuses on generalities and principles, as many of the details of particular risks are project-specific. The specific risks exclusively associated with capture,

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transportation, and storage are excluded from this evaluation and are dealt with by the respective working groups of ISO/TC 265 in appropriate documents and reports.

6.2 Identification of overarching and crosscutting risks over the lifecycle of CCS projects

Table 3 in 5.2.2 was the result of extensive discussion among CCS experts and risk analysis experts from within and beyond ISO/TC 265. This clause is designed to correspond to the most prominent risks identified.

6.3 Overarching risks

6.3.1 Over-arching risks[4)]

Overarching, or overall risks are risks that affect the entire CCS project.

Over-arching risks can also be split into three types, **commercial**, **stakeholder**, and **design and construction**.

- **Commercial**
  - delays in obtaining, refusal, or the application of onerous conditions for consents;
  - construction delay affects project cash flow;
  - land issues related to ownership and access (delay, cost, terms, non-availability);
  - land issues related to environmental and site conditions;
  - cost overruns due to increased price of indispensable factors;
  - availability of suitable contractors, expertise, and/or skills;
  - availability of components and hardware;
  - Force Majeure affecting time, cost performance, and viability;
  - litigation;
  - availability and price of debt;
  - delays due to industrial action;
  - interest rate changes;
  - exchange rate risk for imported materials or equipment;
  - developer credit risk.
- **Stakeholder**
  - public opposition;
  - land issues related to ownership and access (delay, cost, terms, non-availability);
  - providing assurances for environmental and site conditions along the route;
- **Design and construction**
  - unavailability of suitable design standards;

4) Defined as "risks that are truly outside of the capture, transport, and storage elements of a CCS project chain".

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— design problems raise significant CCS technical issues;
— unexpected land contamination;
— land issues related to access;
— unavailability of suitable expertise and/or skills;
— late or unavailability of hardware (e.g. steel availability or capacity in rolling mills);
— unexpected archaeological discoveries;
— unexpected environmental issues (rare flora or fauna discovered);
— criminal or intentional damage;
— delays due to inclement weather;
— poor quality assurance during construction;
— accidental fatality on site.

6.3.2 Policy uncertainties

6.3.2.1 Context

CCS deployment will be driven through government policies [International Energy Agency (IEA), 2012]. Government policies relevant to CCS include: laws and regulations, international agreements, emission control policies, access to transportation infrastructure, storage sites and pore space, environmental protection requirements, monitoring requirements, liability obligations, resource use priorities (e.g. groundwater, oil and gas, coal etc.), taxation, industry incentives, subsidies and promotion, and infrastructure development. Strong financial and policy action may be required by governments to overcome obstacles to private investment, including the technology risks associated with early mover projects, relatively high capital and operating costs, and the lack of direct cost benefit to undertaking CCS in the absence of a punitive price on CO_2 emissions. Government action may also be required to stimulate new markets, to address market barriers and failures, and to promote infrastructure development in support of deployment. Because of their high cost and long operational lives, CCS assets are particularly sensitive to policy risk.

General policy risks and uncertainties include:

— inadequate policy support for CCS;
— gaps in CCS policy, laws and regulations;
— inadequate policy detail;
— misinformed or excessive regulatory burden;
— regulatory conflicts between government bodies with legal authority over a project;
— lack of experience or precedence with implementation of policies, laws, and regulations;
— inconsistent or unpredictable enforcement of laws and regulations;
— changes to existing policy detail or policy priorities;
— unexpected delays in providing necessary approvals;
— fiduciary uncertainty and requirements.

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Impacts of policy uncertainty include:

— project delays, resulting in additional costs or cancellation of the project;

— escalation in project cost due to compliance with overly cumbersome regulations or risk-aversion where regulation is ambiguous or inconsistently applied;

— underperformance by operators who seek to test the scope of the regulations. This may result in lower costs for the operator in the short term, but may lead to adverse outcomes for the environment, the community, the operator, and the reputation of the CCS industry;

— higher risk premiums, in the form of higher interest rates charged for financing CCS projects to cover contingencies for uncertainties.

6.3.2.2 Examples

The lack of a clearly-communicated, coordinated government position on CCS deployment is recognized as one of the factors that contributed to the abandonment of the Dutch Barendrecht project in 2010. Differences in policy are brought into sharp focus when storage sites straddle jurisdictions (i.e. transboundary storage), or when approval is sought to transport CO_2 across jurisdictional boundaries.

While substantial progress has been made in some jurisdictions to enact laws, regulations, and guidelines to support CCS activities, there are many policies that have yet to be properly tested or clearly detailed by policy makers, as happened with the UK CCS Commercialisation Programme in 2015. Regulatory gaps are possible in even the most advanced regulatory regimes. Policies will change over time with experience, changing priorities and expectations, depending on how CCS and competing low emission technologies develop. CCS developers and operators therefore evaluate the impact of existing policy, identify gaps, and consider adopting contingencies for change based on likelihood and potential impact. In a changing policy environment, businesses monitor policy developments in order to anticipate changes that may impact their business. Governments can provide more certainty to industry by setting clearly defined breakpoints or gateways that indicate when or if policy will move to a further stage.

6.3.2.3 Conclusions

The economics of CCS would improve, and uncertainties and risks would be reduced, if CCS projects were operated under consistent, policies, principles and rules in most, if not all, jurisdictions. Experiences and best practices achieved in one jurisdiction could then be more easily applied for the benefit of projects in other jurisdictions. Harmonization of rules would be of greatest benefit for jurisdictions with the least experience with CCS projects, providing greater certainty, lower risk, and a significant head start on the learning and cost curves.

6.3.3 Uncertain cost or regulations for integrated project

6.3.3.1 Context

Uncertainty in cost of construction and operation as well as in costs associated with closure and post closure affect the potential implementation of an integrated CCS project. Changes in costs of materials and services result in changes in the overall cost of a project.

Regulatory approvals of construction and operating permits for the capture, pipeline, wells and storage components are critical pre-requisites which enable the implementation of any CCS project. The absence of regulatory "directives" for CCS projects may cause significant impact to the regulatory timeline in any jurisdiction, which adds cost from a project developer's perspective.

6.3.3.2 Examples

There may be risks to project scheduling due to the immaturity of key aspects of the legislative and regulatory regime for carbon capture and storage in any jurisdiction (e.g. subsurface storage, pore space

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resource). For example, failure to secure adequate pore space resource under the mineral property laws and in conjunction with competing uses of the subsurface under an appropriate regulatory framework, would also represent significant risks for permitting commercial-scale integrated CCS operations. Integrated CCS projects that are added to existing facilities may result in increased oversight and an expanding scope of the regulatory process to include examination of the existing facility and operations.

6.3.4 Engagement

6.3.4.1 Context

Public engagement can impact the entire CCS project chain at any point in a project lifecycle (overarching risk). For example, public support or opposition in the opportunity, planning, and engineering phase can influence whether or not a project goes forward. During the operational phases, issues around public disclosure of data can impact a project, or a safety-related incident at any CCS project could create a requirement for operations to cease until the nature of the events that led to the incident have been ascertained, so that similar occurrences might be avoided. Risk communication may be conducted at different stages of a CCS project, and may be especially important when approaching closure and/or post-closure.

Best practices for public engagement in CCS have been published and provide resources aimed at identifying and managing the risks associated with engaging the public on CCS. These documents also include case study examples of public engagement in CCS for successful and unsuccessful projects. For example, see Guidelines for Community Engagement in Carbon dioxide Capture, Transportation, and Storage (World Resources Institute (WRI, 2010), Public Outreach and Education for Carbon Storage Projects [National Energy Technology Laboratory (NETL), 2009], Communication/Engagement Toolkit for CCS Projects (GCCSI and CSIRO, 2011), Communications for Carbon Capture and Storage: Identifying the Benefits, Managing the Risk, and maintaining the Trust of Stakeholders (GCCSI, 2013a), ESTEEM: Engage Stakeholders through a Systematic Toolbox to Manage New Energy Projects (EU 5108351, 2009), Social Site Characterization and Stakeholder Management(GCCSI, 2013b), Qualitative and Quantitative Social Site Characterizations (SiteChar, 2011). There are also numerous peer-reviewed articles on this topic.

6.3.4.2 Examples

By following best practices for public engagement and effectively engaging host communities CCS can build trust between the public and a project operator, effective public engagement does not ensure public support for a CCS effort. Case studies describing experiences in engagement on CCS have been published by the World Resources Institute (WRI, 2010) and the Global CCS Institute (GCCSI, 2014, 2012, 2010b, c, d). These case studies describe the engagement strategy and outcomes at various projects, including CCS projects that faced opposition and did not go forward for a variety of reasons such as Barendrecht (Shell) and FutureGen (FutureGen Alliance). These case studies also cover successful CCS projects including the Illinois Basin Decatur Project (ISGS) and Otway (CO2CRC). There have also been recent (2015) publications in the peer reviewed literature describing the issues with public engagement on CCS in Germany and the role the media has played in these projects (Pietzner, 2015 and Dütschke, 2015).

6.3.4.3 Conclusions

Guidelines and processes have been established for public engagement in CCS projects and are available to the project developer, including ISO 26000 Social Responsibility standards for public engagement.

6.3.5 Project permits not obtained

6.3.5.1 Context

While the issue around regulatory uncertainty impacts all phases of an integrated CCS project, the risk around a failure to obtain project permits can be related to other technical issues associated with a CCS project.

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6.3.5.2 Examples

For instance, the permitting authority (i.e. government) is not satisfied that adequate design margins have been included to reduce risk to an acceptable level. Also permits for drilling and injection might be refused or significantly delayed due to negative project perception. Issues such as surface owners objecting to seismic surveys, for instance, can have a consequential impact on the permitting process. A CCS project proponent's inability to convince stakeholders of the long-term performance of the storage system can also impact permits approvals. An inability to demonstrate storage feasibility (i.e. containment, injectivity and capacity), and inappropriate pore space and injection site selection clearly poses a serious threat to project permit approvals. Permits will be difficult to obtain if issues such as late stakeholder engagement, provision of misleading and/or conflicting information and a real or perceived lack of knowledge and understanding of CCS, CO_2 toxicity, etc. occur within the CCS project management. In some cases the correct decision will be to not permit the project.

6.3.6 Lack of or changes in financial driver

6.3.6.1 Context

The availability of adequate government incentives that create value for CCS alone currently represents a very uncertain market driver for financing CCS projects in most, if not all, jurisdictions. This uncertainty spans all CCS project elements and the associated investments in equipment and infrastructure for capture, transportation, and storage of CO_2. In most cases, however, it is anticipated that there will eventually be some mechanism of credits or route to deriving value for the capturing and storing of CO_2. This risk includes continued uncertainty regarding whether the incentive regime may allow for a decline in value of previously granted incentives or credits below the financial assumptions around which a CCS project is developed. The value a CCS project might be reduced if for example CCS credits were not tradable at fair market value as a result of restrictive or additional GHG regulations. In addition, uncertainty may result in the price of CO_2 dropping to non-economic levels during project operation. During the life of a CCS project, CO_2 may have a higher value use (other than direct storage) elsewhere such as being transported to a CO_2 EOR project. Ultimately, the extent to which changes in the financial driver are shared between elements in the CCS chain will have a substantial impact on risk.

There is an element of regulatory risk embodied in the financial risks a CCS project may face. For example, a change to regulations or policy around issues such as well abandonment requirements, taxes or the cost of carbon dioxide emissions or the regulators not allowing incidental storage in association with enhanced oil recovery (EOR) to be recognized as a CO_2 storage project may have a significant impact on the financial viability of a CCS project. Local market changes within any jurisdiction or a large rise or fall in oil prices may affect also the financial viability of a CCS project relying on sales of captured CO_2 for use in CO_2-EOR operations.

6.3.6.2 Examples

The risks of uncertain financing were underscored in December 2015, when UK government cancelled £1 billion in funding for CCS projects. The announcement halted both the White Rose (National Grid Carbon) and Peterhead-Goldeneye (Shell) projects. The announcement also led to a massive reduction in interest, and the abandonment of most UK CCS project developments.

In China, Sinopec has intended to scale up Shengli Oilfield EOR pilot test since 2013, however further action is pending, due to the fall in oil prices and the lack of other financial drivers.

In the context of the Weyburn CCS project, this risk has resulted in a change in the project economics resulting in the target volume of CO_2 not being stored. Such a change in project economics could be brought about for a variety of reasons including:

— a change in project economics during the transition from EOR to storage (e.g. changes in cost and revenue structures, or the injection rate of CO_2 stream as oil extraction reduces);

— a change to regulations or policy (e.g. well abandonment requirements, taxes, cost of carbon);

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— a change to the value of storing CO_2 (e.g. CO_2 may have a higher value use elsewhere such as being transported to another EOR project);

— regulators will not allow EOR to be recognized as a CO_2 storage project;

— lack of financial driver.

6.3.6.3 Conclusion

Premature closure of the site or cancellation of a CCS project may be driven by a number of factors including:

— closure of the CO_2 capture source for financial, operational or other reasons;

— changes in project economics.

6.3.7 Changes in financial factors external to the project/Insufficient project financial resources/Changes to the cost of capital

6.3.7.1 Context

Sufficient financing is key to any successful commercial-scale integrated CCS project. Given the early development stage of CCS technologies and lack of market incentives for climate mitigation technologies, financing large-scale CCS projects is both challenging and complicated. Therefore, any first-of-a-kind CCS project is likely to rely heavily on direct or indirect subsidies, or other forms of financial support. Financing a CCS project generally requires two types of financing mechanisms. The first type is aimed mainly at reducing investment costs before the project is approved and during early years of construction, and includes grants, government loans, subsidies, and tax investment exemptions. The second is intended to increase revenues or otherwise improve cash flow during the operational phase of the project, is mainly relevant for commercial-scale projects or mature technologies with known costs, and operates mainly through a market mechanism, like carbon trading, and CO_2-EOR. Different stages of CCS project development also involve different financing combinations and primary investors (see Figure 8). For demonstration projects, a combination of public support and entrepreneurial activity is required, while traditional investors and capital markets generally take the lead for commercial CCS projects.

6.3.7.2 Examples

In the case of SaskPower's Boundary Dam Project, (currently the world's only operational CCS project in the power sector), the total cost of the project was \$1,3 billion. SaskPower received \$240 million from the government for part of the project's capital expenditures and paid an additional \$1 billion in capital costs itself. However, given that SaskPower is owned by the province of Saskatchewan, the entire project was effectively Government funded. Operational costs for the plant are financed in part through the sale of captured CO_2 to Cenovus Energy for enhanced oil recovery under a 10-year agreement.

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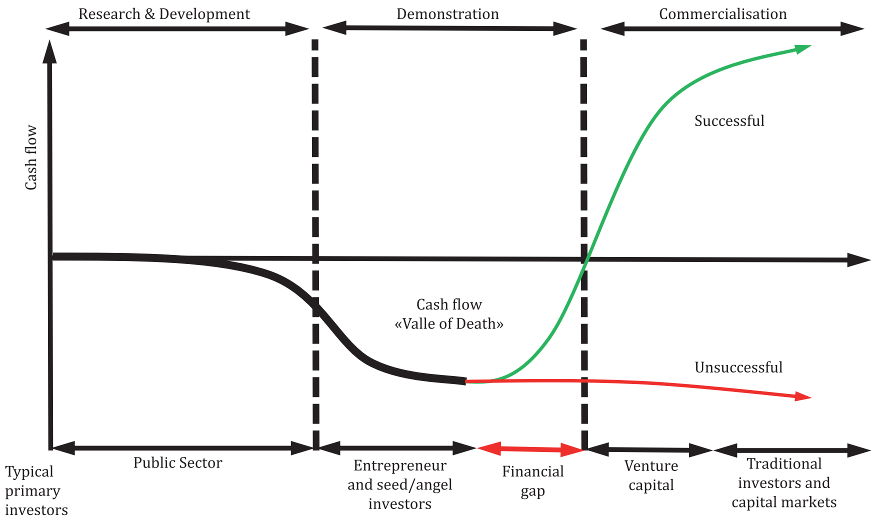

Figure 8 — The Cash Flow "Valley of Death" as a function of development stage with typical investors shown for the various stages (Murphy and Edwards, 2003)

6.3.7.3 Conclusion

CCS projects cannot reach construction or operational project phases without sufficient financial resources.

6.3.8 Unexpected construction or operational cost changes

6.3.8.1 Context

Unexpected construction or operational cost changes can also lead to insufficient project finance, which may eventually lead to a project delay or cancellation.

6.3.8.2 Examples

For example, for its Kemper County IGCC+CCS project (USA), Southern Company received a $270 million grant from the US Department of Energy under the Clean Coal Power Initiative Phase II and $133 million in investment tax credits approved by the Internal Revenue Service. Nevertheless, because it missed its original deadline of putting the plant into operation by May 2014, Mississippi Power (owned by Southern Company) had to repay the tax credits to the federal government.

Project delays and cost increases go hand to hand: the initial estimated project cost of the Kemper project has been raised to $6,3 billion from an original $2,4 billion, due to a number of factors, including regulatory issues, engineering problems with the pipe construction, and lack of experience in design and construction of an IGCC plant. In July 2016, the Kemper County IGCC produced its first syngas.

6.3.8.3 Conclusion

When planning and designing early CCS projects, it is critical for project owners to prepare financing plans that incorporate, or at least recognize, the possibility of unexpected regulatory and cost changes.

6.3.9 Uncertainty in CO_2 supply

6.3.9.1 Context

In the planning phase, lifecycle design and plant layouts are made for the technical infrastructure of an integrated CCS project. The actual CO_2 stream supply volumes at the time of operation may differ

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from the initial planning. It can be either lower or higher and the mismatch between planned and actual supply can affect:

— capture, transport, and injection rates, operability of technical infrastructure;

— utilization of the storage capacity of a reservoir;

— planned lifetime of infrastructure and overall project life time.

As a consequence of changes such as these, the operational costs and the cost per tonne of CO_2 emissions avoided can diverge from the initial economic calculations.

6.3.9.2 Examples

Preliminary contracts for CO_2 supply may be signed during project planning. These contracts may be internal management agreements in enterprises holding upstream and downstream companies, so that the entire integrated CCS project is within one organization. Another business model could be contracts made with external business partners willing to supply CO_2 from CCS applications. There are many possible reasons for enterprises changing their initial intentions or being unable to meet the contractually agreed supply. Markets may develop differently from what was originally expected. For example in Europe, the regulation of the market for CO_2 emission certificates according to the Directive 2003/87/EC (EU, 2009; EU, 2003) on the European Certificate Emission Trading Scheme (EC ETS) led to certificate prices well below expectations and below those prices needed for economically viable CCS projects. The low certificate prices were one of the main reasons for companies in Europe to withdraw CCS plans, applications or permits granted for storage site exploration. However, high prices for certificates or a carbon tax might lead to “carbon leakage” to other countries. The term “Carbon leakage” does not indicate physical leakage, but signifies a situation in which, as a result of stringent climate policies, companies move their CO_2-generating production to countries with less restrictive measures. While apparently reducing emissions in the host country, the movement of production to less efficient systems abroad can lead to a net rise in global CO_2 emissions.

Technical developments could create alternative solutions for CO_2 emission reductions, that may be more attractive financially, technically and energetically, as well as less risky and more acceptable to stakeholders than CCS. Hence, these alternative options might be favoured when the integrated CCS project actually commences operation. The CO_2 supply may also be reduced because an enterprise changes its strategic direction and portfolio of products and companies, or plainly suffers bankruptcy. In contrast, more CO_2 than planned may be available from the source. This could be the case for example in Europe, where Article 21 of directive 2009/31/EC requires non-discriminatory access to transport and storage infrastructure for third parties.

Generally, economic risks exist when technical facilities with differences in expected lifetime and business cycles are combined in CCS systems. Plant operation times may be shorter than life-time for filling large CO_2 reservoirs, such as the “CO_2 superstore” suggested by National Grid, offshore in the UK. Large scale transport and storage infrastructure may be planned to be provided and offered by one operator to a variety of possible CO_2 sources, needed to achieve technically and economically efficient transport and storage rates.

6.3.9.3 Conclusions

A number of technical and administrative provisions have been described which have the potential to reduce the risks associated with uncertainties in the supply of CO_2. These include:

— placing contracts for CO_2 supply which take into account counterparty credit and performance risk, and

— ensuring that contracts contain clauses addressing such matters, including, for example, compensation for deviations from the agreed supply. In such cases, the parties may consider reinsurance of financial risks.

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Technical considerations for reducing risks of CO_2 supply could include networks collecting CO_2 from a variety of sources or obtaining CO_2 from a source in an industrial region, offering potential for substitutes, in case a supplier is no longer able to meet their contractual obligations.

6.3.10 Lack of emissions accounting

6.3.10.1 Context

Emissions accounting is used in part to build public confidence in CCS as a climate mitigation approach and accounting protocols have been developed to support the inclusion of CCS in the national inventories that countries submit to the Intergovernmental Panel for Climate Change (IPCC, 2006) as well as to national and sub-national greenhouse gas reporting programs (EPA, 2016) and non-profit organizations (e.g. American Carbon Registry, 2016). Failure to account for CO_2 emissions can result in the reputation of a company being tarnished, leading to public opposition to continued operation as well as financial risks associated with failure to receive Certified Emission Reduction (CER) credits (for example under the Clean Development Mechanism or national tax program). The lack of emissions accounting is an overarching risk that affects the whole CCS project chain, primarily during the operational and closure phases. Following an established CCS-specific emissions accounting framework helps address this risk.

6.3.10.2 Examples

Recently questions have been raised regarding the acceptance of negative emissions credit for bioenergy with CCS in the context of the European Union’s Emissions Trading Scheme (EU ETS (Kemper, 2014). In the United States, California is undergoing the process of establishing a quantification protocol for CCS which would enable accounting in the California ETS.

6.3.10.3 Conclusions

Frameworks are available and in use, designed to enable the accounting of emissions reductions associated with CCS at the national to project-specific levels.

6.3.11 Technology scale-up

6.3.11.1 Context

There are risks associated with scaling up any new technology, and this represents uncertainties for future projects. For example, many of the capture technologies have been either used in other industries or demonstrated at large scale. As these approaches are extended for use on commercial scale projects, the processes will need to be redesigned and optimized for full-scale efficiency. The uncertainties around technology scale-up may affect the entire CCS project chain and are best described as an overarching risk that is most apparent during the start-up (engineering and construction) and operational phases (capture, injection). There are two distinct classes of impacts stemming from poor performance of new technology which results from technology scale-up risk:

a) impacts on safety or project economics;

b) impacts on public opinions of CCS.

6.3.11.2 Examples

Technology scale-up risk is often echoed by the media in reports of delayed or underperforming operations during project start-up and early operations. These reports can affect public and academic attitudes regarding specific CCS approaches. Examples of such reports include delayed start-up and cost overruns at the Kemper County IGCC in Mississippi, United States as well as in the poor reliability of the capture unit at Boundary Dam in Saskatchewan, Canada. In addition to the impact on public opinion of CCS, there are also practical impacts on the project such as a delay in the planned emissions reduction or increased cost associated with a delay.

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6.3.11.3 Conclusions

Large-scale demonstrations can reduce scale-up risk, but some process improvement and necessary shut down should be expected for first-of-a-kind facilities. Adopting transparent communications and outreach about such learnings during engagement with various stakeholders can help to build trust.

6.3.12 Lack of knowledge or qualified resources for operating the unit

6.3.12.1 Context

Periods of high activity with other associated or competing energy projects, or consolidation of the market place may not only result in financial pressures on a CCS project but could also give rise to a significant shortage of skilled labour. CCS project operators generally will strive to achieve economic maximum production and cost effective operating performance, management of all risks and position themselves to capture opportunities for their respective CCS project(s). To achieve this, qualified labour is a requirement. Attempting project execution without the appropriate skills can lead to schedule delays, cost overruns and potential health, safety and environment issues.

6.3.12.2 Examples

Loss of institutional knowledge and/or experienced field personnel can result in significant delays while training occurs. Delays can interrupt scheduled MVA activities which might result in permit violations. Skilled field personnel are needed for sampling, site maintenance, laboratory analysis, analysis interpretation and quality control, and report preparation. Skilled individuals often have a MS degree in geology, hydrogeology, soil science, chemical engineering, mechanical engineering, chemistry, fluid dynamics, or similar discipline. These challenges have been experienced and managed at the Illinois Basin Decatur CCS project in the United States.

6.3.12.3 Conclusions

Risks associated with the lack of qualified resources or loss of key project personnel can be anticipated and managed to avoid impacts on the CCS effort.

6.3.13 Project impacts on the environment

6.3.13.1 Context

Potential impacts an integrated CCS project may have on the environment includes impacts to air quality, biological organisms (plants and animals), soils, land use, surface waters, the viewshed, and cultural and historical resources. Any large energy project will have some degree of impact on the environment, and it is important that local or regional regulations for Environmental Impact Assessments (EIAs) are followed. In some jurisdictions, an EIA may not be required. For example, in Alberta, Canada the addition of CCS to an existing project would not require an EIA—different places will have different criteria and exemptions from the EIA process. An environmental impact assessment can help identify significant and potentially significant environmental impacts and provide a clear process for determining appropriate mitigations. The environmental impact assessment is usually carried out during the planning and engineering phase of a project (often a requirement for governmental approval to begin a project), however environmental impacts can also occur during operation, closure, and post-closure periods. Environmental impacts can also happen at or in-between any point in the capture, transportation, and storage project chain. As noted in the introduction, the risk assessment can be integral to the EIA.

6.3.13.2 Examples

Examples of an EIA or Environmental Impact Statement (EIS) that have been developed for CCS projects and include such risk analysis include: the Gorgon (Chevron) Project in Australia and the FutureGen (FutureGen Alliance) Project in Illinois.

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6.3.13.3 Conclusions

6.3.14 External natural impacts on project

Risks associated with environmental impacts of a project can be reduced by carrying out an EIA where the potentially significant impacts are identified and mitigation measures are identified and then subsequently implemented. Although external natural impacts may affect primarily a single project component as in the examples below, they can impact a CCS project throughout the whole project chain and lifecycle.

6.3.14.1 Examples of external natural impacts on project

Capture: A CO_2 capture facility is vulnerable to external impacts from weather (temperature change, wind, severe weather, etc.) as well as natural disasters (earthquakes, floods, etc.). Ambient-air temperature increases require increased energy for compression. Sudden or extreme temperature changes can cause CO_2 phase changes (liquid, gaseous, dense) in surface or subsurface facilities, causing rapid changes in flow characteristics.

Transportation: Buried pipelines are particularly vulnerable to ground movement, such as might be experienced during an earthquake. The 1971 San Fernando earthquake caused the rupture and/or buckling of several water, gas and sewage pipelines (Ariman, 1983), some of which were large diameter (up to 16", 406 mm), but fortunately low pressure (150 psi, 10 bar) compared to that expected for CCS applications. During late 1982 and early 1983 intense, prolonged rainfall associated with the El Niño-Southern Oscillation (ENSO) phenomenon brought severe floods and landslides to many coastal regions of Ecuador. There was significant damage caused to water and sewage pipelines, pumps and networks (Few and Matthies, 2006). Flash or high velocity floods are the most damaging because their force can knock out pumping installations.

Storage: For CO_2 storage, an external event could reactivate a fault if reservoir pressure or thermal stress exceeds the fault strength. This could yield migration along a stratigraphic pathway: As a result of the structural features in the subsurface, in particular, the caprock, a stratigraphic pathway may exist for brine or CO_2 migration out of the primary containment complex. More extensive measurement monitoring and verification (MMV) measures may be required, injection may need to be cut back or redistributed, potentially over additional wells, and CO_2 credits could be lost if uncontained volumes of CO_2 incur penalties or result in loss of credit. If loss of containment remains undetected contamination of potable water zones and leakage to surface may eventually result which could endanger public health and safety, cause environmental damage, legal action, and considerable loss of reputation.

6.3.14.2 Conclusions

Consider the potential for external natural impacts to impact a CCS project throughout the whole project chain and lifecycle, to include potential geological discontinuities and seismic events. Extreme natural events should be considered in a risk assessment for each element of the CCS project chain.

6.3.15 External man-made impacts on project

6.3.15.1 Context

Man-made impacts (including pre-existing wells) can also affect an overall CCS project through the whole project chain and lifecycle.

Future CO_2 injection sites that are geologically connected with a pre-existing injection and storage site could reduce the pore space capacity available to original project both injection projects. Incremental injections into the same injection horizon in a geologically connected formation could elevate the pressure in that area and reduce capacity and injectivity. The consequence of this scenario may be that additional infill wells are required away from the adjacent CCS scheme but within the region of influence to maintain injectivity and to compensate for loss of storage capacity. Extra pipeline and/or laterals may be required to provide maximum offset to the adjacent CCS scheme.

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6.3.15.2 Examples

Capture: Examples of man-made factors that could create risk for the capture plant include a human error which causes a plant shutdown, missed maintenance, or an unrelated accident that occurs at an adjacent plant or unit.

Transportation: Third party interference to transportation infrastructure is statistically the most common cause of inadvertent product loss, for instance puncturing a buried CO_2 pipeline during earthmoving operations [e.g. on the Jackson Dome Tinsley CO_2 (Delta) 8" pipeline].

Storage: A third party may drill though a storage formation or cause changes in the subsurface pressure distribution by producing or injecting fluids nearby. Another possible impact in a storage site could result from migration along legacy wells. Inadequate integrity of pre-existing wells traversing the injection formation could provide a migration path across the seals of the CCS project storage complex. This could cause brine intrusions. Such failure of integrity could result for example, because of the way the pre-existing well was drilled, completed or plugged and abandoned. As a result, brine or CO_2 could leak to either shallower horizons or, ultimately, to the surface if the pressure front induces fluid migration up-hole or the CO_2 plume intersects these wells. Additional cost may be incurred towards remedial action on wells with poor integrity, to implement a requirement to redirect the plume away from offending well. More extensive MMV measures may be required and CO_2 credits could be lost as leaked volumes would incur penalties. If a breach remains undetected, eventually contamination of potable water zones and leakage to surface may result, which could trigger litigation, HSE issues and damage reputation.

Injection induced stress fractures geological seals: If injection-induced hydraulic and thermal stress (cold CO_2) were to exceed the fracture stress of the geological seals, for instance due to operational error or uncertainties on actual fracture pressure for the caprocks identified for the CCS project, then geological seals could be fractured.

Third party activities may induce environmental changes that cannot be distinguished from the potential impacts of CO_2 storage that might trigger a perceived loss of containment from the CO_2 storage complex.

6.3.16 Conflicts with other land-use rights

There is potential for conflicts with existing land use or uncertainty in the land use impacts associated with a planned project to affect CCS project through the whole project chain and lifecycle. Although there are limits to which aspects of land use uncertainty can be addressed as part of a risk assessment, inclusion of these risks can enable a more robust risk assessment effort.

6.3.16.1 Context

CCS operators may have conflicts with other users of the surface or the underground at capture, transport or storage sites. Stakeholders on the surface include land owners (mainly farmers in rural areas), and more generally people living close to CCS locations or pipeline routes. Stakeholders of the underground include owners of the affected subsurface formations (public or private) and operators of usages other than for CO_2 storage: e.g. natural gas storage, underground energy storage, geothermal plants, radioactive waste disposal, groundwater extraction, oil and gas production operations, and mines[5]. The criteria for risk evaluation of this uncertainty include the potential for degrading HSE aspects of the project and/or performance modification and/or stopping the underground exploitation.

Conflicts of use are differentiated below according to their typical occurrence during the pre-operational phase vs. the operational phase. Once a project is closed, it is assumed that each physical component of the CCS project is independent from the others.

5) CO_2 storage can be combined in a beneficial way with another use such as oil and gas production (EOR), heat extraction, or saline water production (EWR).

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6.3.16.2 Examples

6.3.16.2.1 Pre-operational phase

During the pre-operational phase, conflicts with other users may arise from modifications to the initial state by construction of the CCS facilities. In the case of capture, construction of the specific capture installation implies the extension of the power plants or other CO_2 emitting industry, which could impact on landowners and nearby land use[6)]For transportation, the identification of the path of the pipeline requires negotiation with land owners and identification of the juridical status of the portion of land bearing the transport facilities (public easement, rent to landowners). Concerning storage, the occupation of surface facilities and well pads has also to be negotiated with land owners, as well as the areas used for monitoring (even if the occupation is temporary, e.g. seismic surveys). In the subsurface, conflicts may be the result of the vicinity of other pre-existing underground users (see list in Context), aiming at using either the same pore volume or the caprock bearing shale gas (or oil). Conflicts could be the consequence of underground plume extension or pressure and temperature change beyond permitted area or beyond areas covered by contracts with owners of surface or subsurface rights.

In case of refusal by landowners, the whole project could be stopped for a while, until a solution is found, either financial or by exchange of properties. The development of a project could also be halted if underground users in the vicinity consider that the development of a storage project negatively impacts their assets. In that case, the project operator should demonstrate that the CO_2 plume maximal extension, altogether with pressure and temperature changes or any other impact, do not affect other users. Any leakage through a well or a fault should be avoided in order to prevent any interaction with other users. Another option for the project operator facing this risk would be to continue the project, but arrange for appropriate compensation or leasing of storage rights.

There may also be conflicts with existing land use that result in an inability to determine the baseline environmental data needed for monitoring.

6.3.16.2.2 Operational phase

During the operational phase, impacts on other users related to capture or transport are limited to specific impacts such as noise, air quality, apart from an accidental release of CO_2. The latter being treated as a risk specific to capture or transport. A new land use planning could result in a conflict between the construction of a facility, e.g. a new road or public building, and the pipeline path. At the storage site, conflicts with land owners or farmers should be resolved during the preoperational phase. Nevertheless, they could possibly happen in case of a suspected leak of CO_2 or need for new monitoring survey places. Examples of underground impacts on other users include plume extension or pressure or temperature change beyond permitted areas or beyond areas covered by contracts with owners of subsurface or subsurface rights, contamination of drinking water aquifers by the CO_2 stream, cooling of geothermal resources, etc.

6.3.16.3 Conclusion

Project developers will need to be aware of the potential for governing CCS construction and operation to have an impact on the owners and users of adjacent land assets, both above- and below-ground.

Risk treatment during the pre-operational phase:

— To get the project running regarding capture and transport, dealing with the land owners and getting public acceptability in the vicinity and surroundings are essential. An appropriate regulatory framework may be used to obtain access to land (depending on local regulations). Respect to storage, site screening (i.e. establishing a first list of possible areas) needs to take into account the proximity of other underground users, on either a vertical dimension (mainly for potable water aquifers) or the horizontal one (geothermal, gas storage, hydrocarbon exploitation, mines etc.). Once the site is selected, site performance analysis and modelling of risk scenarios allow evaluation of the maximum plume extension and consequently possible interactions with other underground

6) Not necessary in case of capture-ready plant.

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exploitations. Modification to the initial project should be made to minimize risk of conflicts with other users. A characterization report should be made available for the regulators, stakeholders, public and relevant NGOs. Regulations and standards for conflicts of use, if any, should be properly applied.

— For risk treatment during the operational phase regarding capture and transport, the same comments apply as those for risk identification because any potential conflicts with land owners or farmers that could affect the project are managed in the framework of other overarching risks. With respect to storage, careful monitoring of the plume extension is needed to detect any migration close to another underground exploitation or a leakage up to a potable aquifer. In case of proven impact, the operator needs to apply the corrective measures included in the storage risk management plan, e.g. to decrease or stop the injection, or even back-produce CO_2.

6.4 Crosscutting risks

6.4.1 General

Crosscutting risks are risks that affect more than one part of a CCS project chain. Integration risks are considered crosscutting for the purposes of this document.

CCS systems, composed of multiple sources and/or reservoirs, are more complex than simple “point-to-point” CCS projects comprising a single source and sink. This is especially true if the latter is organized by a single operator. As systems incorporate additional sources of CO_2 linked to additional reservoirs, care is required to minimize the potential impact of potential variations in the composition of CO_2 streams from multiple sources from different operators. For example, the simultaneous increase of moisture in one stream and pressure drop in another stream could increase the risk of condensation in the combined CO_2 stream. With respect to qualitative and quantitative variations of CO_2 streams, it may be appropriate to distinguish single source-sink projects from small and large CCS systems (or infrastructure) for the management of overarching and crosscutting risks.

Single source-sink CCS projects: In a simple process chain, connecting one source with one sink, any standstill or decreased performance affects the entire process efficiency, and within a given time period at least, the amount of CO_2 stored and avoided. Complex legal, technical, and financial situations resulting from the combination of various CO_2 streams can be avoided and the comprehensive management of overarching risks may be easier. Necessary maintenance periods of technical infrastructure may be planned well in advance and compositional changes resulting from the blending of CO_2 streams from various sources do not need to be considered. On the other hand, the designer has the option to specify the product stream according to his own criteria, for instance choosing to transport CO_2 with a high moisture content through stainless steel pipelines, rather than dehumidify the CO_2 stream and use lower-cost carbon steel pipeline materials.

Extensive CCS infrastructures: Extensive CCS networks including various sources and sinks, connected by a transportation grid would offer the greatest flexibility for coping with disturbances at technical installations or within storage reservoirs, as alternative sources, transport options, and storages are available and could be used for switching and alternate routing within the network, so that bottlenecks arising from failures at single points could be bypassed. Downstream, a pipeline grid and a cluster of storage sites would provide buffer capacity for temporarily elevated fluxes of CO_2 streams. In a blending of various gas streams, it may be possible for composition changes of the stream coming from one particular source to be attenuated (note that in this case, the overall composition of the CO_2 stream needs to be monitored carefully to ensure that the combined product does not breach impurity limits). However, management of such an infrastructure network and temporal alignment of the production and CO_2 capture from independent companies will be a complex task (Middleton et al., 2013). High investments for extensive CCS infrastructure will probably be restricted to storage associated with enhanced oil recovery or possibly other CO_2 utilization such as coal bed methane and shale gas production if their technical and economic feasibility is proven. Economies of scale may create markets for such large systems even though there may be more regulatory requirements in the future. Numerical models are considered useful for risk assessment, performance planning, and operation of such extensive networks, including planning of preventive measures in case the flux or composition of the CO_2 stream falls out of the operational window at some installation at some time.

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Small CCS systems: Small systems, combining a few sources and sinks only, may be the most vulnerable to changes of CO_2 stream compositions arising from mixing of different streams from various sources. The composition changes may be large, while the flexibility of the system may be low because of the limited number of sources, sinks, and transportation options and hence only limited options to compensate any disturbance. Including large “base-load” sources may help to cope with qualitative variations. However, overall fluxes will be controlled by such large sources and may not be adequately compensated by a bundle of smaller CO_2 sources, when the large source is out of operation.

Enlarging the operational windows of capture, transport, and injection facilities in order to cope with more variable CO_2 stream composition and flux may increase costs and reduce efficiency of installations. Hence, selecting single source-sink solutions or a wise mix of CO_2 sources, transportation, and storage options, as mentioned for OA economical risks resulting from uncertain supply (see 6.4.2.1), can be used for risk reduction. A wise mix may mean sources of CO_2 that are similar in their production and capture technologies and carbon source used. Switching CO_2 streams from one reservoir to another should take into account the specifications of transport and injection infrastructure and reservoir and caprock lithologies in order to avoid unwanted chemical reactions.

6.4.2 Accidental or intentional interruption or intermittency of CO_2 supply, CO_2 intake or transportation

6.4.2.1 Context

(XC, C⇆T⇄S)

The quantity and quality of CO_2 streams might vary with time. Intermittency is a more or less predictable variation, resulting from the technical production process, natural influences, or reflecting predictable variations of power or products demand. Factors affecting power generation from fossil energy sources and related CO_2 emissions might be, for example, energy prices at power exchanges following well known consumers demand profiles, or predictable weather changes that affect solar or wind power generation, which may be given preference in the supply portfolio. Seasonal variations may result from the demand for district heating or cooling power or the processing of perishable biomass after a harvesting season, such as sugar beets. Advanced planning in the design phase for CCS projects can anticipate interruptions and enable CCS projects to be resilient to future changes in the CO_2 fluxes. Planned interruptions may be for maintenance periods, like boiler cleaning, internal pipeline inspections or replacement of liners in injection wells. These interruptions may last hours to months and accordingly could be mitigated by including buffer storage or flexible operation within CCS networks. In particular, in single source-sink CCS systems, longer interruptions lead to interrupted operation of the entire integrated CCS project. Accidental interruptions may equally span variable time scales, with the disadvantage compared to intentional interruptions, that preparatory planning is limited and adaptation to changes can only occur in a reactive (not proactive) manner.

6.4.2.2 Examples

Intermittency of supply may be a problem in the early years of operation of a CO_2 storage reservoir: the associated problems will decrease when the CO_2 plume covers a wider area and the CO_2 stream can disperse more easily in a larger reservoir volume. Intermittent CO_2 supply may also be a problem in CO_2-EOR projects, where the oil production [e.g. by alternating flooding of the oil reservoir by water and CO_2 (WAG)] and CO_2 recycling will dictate the CO_2 demand. Depleted reservoirs that have dropped out of oil production could, as a technical matter, be considered as buffer storages in EOR regions until the termination of the oil production and thereafter, they could be operated in a more regular manner as CO_2 stores, assuming of course what the legal, permitting, and property law framework allows.

Variations of various frequencies add up to the total variation of CO_2 flux and CO_2 stream composition, which, in extended networks, may be different at different locations within the networks.

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6.4.2.3 Conclusions

Risks may result from changing socio-economic conditions, which affect the operation frequency of CO_2 sources, e.g. power plants that used to operate in base or peak load. Increased shares of wind- and solar power in electricity generations requires more flexible load management for both base and peak load power plants, in order to operate profitably. Hence flexibility should be considered in the planning of CCS systems, in order to adapt to such unforeseen changes during the long time periods during which capital is bound in infrastructures of power generation, CO_2 capture, transport and storage. Part of this flexibility can be gained offshore by a combination of pipeline and ship transport, as ships are free to navigate to whatever suitable CO_2 source or terminal is within reasonable reach.

6.4.3 Shared infrastructure by multiple projects (uncertain ownership, performance or lack of coordination)

6.4.3.1 Context

(OA, C⇆T⇄S)

Models (National Grid, 2014) for sharing infrastructure (pipelines and/or storage sites) among power plants and industrial sources are attractive because of the opportunity to share financial risks with other entities (public or private) and more quickly achieve economies of scale. However, shared infrastructure also creates the need for careful coordination and comes with an increased risk (and benefits) to affect the overall project. In the early stages of shared infrastructure development, ownership and coordination may be unclear, affecting the overall risk associated with the project. In some proposed models, the government owns the capture and/or storage infrastructure.

Shared infrastructure can also affect specific elements of the CCS project chain, for example the capture/transportation interface (C⇆T). If multiple CO_2 sources are sharing a pipeline and storage infrastructure, then the sources should be required to limit impurities within the CO_2 to meet the quality specifications of the materials selected for the shared pipeline/storage infrastructure and the pipeline operations. During capture, transport, and storage, underperformance of a capture system at one of the sources may affect the ability to capture CO_2 at another facility, or serve to undermine the compositional basis upon which the safety and performance calculations have been performed.

6.4.3.2 Examples

In North America, some of the existing CO_2 pipelines may receive CO_2 from multiple sources. Like pipeline operators for other commodities (e.g. petroleum, refined petroleum products, natural gas) pipeline operators set CO_2 quality specifications for any CO_2 tendered for transportation in order to mitigate the risks associated with potential corrosion or hazardous co-constituents and ensure that the product meets customer specifications downstream. In some jurisdictions, sources may obtain non-discriminatory access to available capacity, which helps to mitigate the risks associated with accessibility of shared infrastructure, assuming that the applicable capacity allocation rules and practices allow the pipeline operator to honour contractual commitments. The need for sources to supply the CO_2 stream to an agreed composition to minimize the potential for damage to transportation infrastructure is described in some detail in ISO 27913.

The Roadmap for Capture and Storage Demonstration and Deployment in the People’s Republic of China (ADB, 2015) includes a discussion regarding the advantages of risk sharing and public ownership of shared infrastructure.

6.4.3.3 Conclusions

As shared infrastructure is developed, the industry participants may be expected to address these issues as they arise in particular circumstances.

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6.4.4 Using existing facilities

6.4.4.1 Context

(OA/XC, C⇆T⇄S)

It may be possible for existing facilities to be utilized for CCS purposes, however there are inherent risks in doing so. These risks can affect the overall project or cut across any of the specific elements of the CCS project chain (C⇆T⇄S). The condition of pipelines or other infrastructure may be uncertain or not designed to handle dense phase impure CO_2, or the corrosive environment anticipated in CO_2 injection. Hence, where pre-existing natural gas pipeline is to be converted to CO_2 transportation (as has already occurred in the United States), industry participants will review the condition of the pipe, expected operational pressures and related operational matters to minimize these risks.

It is also possible that existing infrastructure may have unclear ownership or the contracts in place that would make it unavailable for CCS purposes. Transitioning facilities from another purpose such as oil and gas production to CCS may also present risks because the timing of the end of the oil and gas project may not match with the timing of completion of a capture project that yields transport or injection-ready CO_2. Moreover, the mineral property arrangements and other aspects of the legal and regulatory framework may not be adapted for such changed purposes.

Operators should be aware that using an National Energy Technology Laboratory (NETL), 2009 existing facility that was originally designed around one, or a number of process fluids to now accept CO_2 from a CCS application may have an impact on the safety case[7)] that accompanied the original installation. Issues that may need to be addressed may include:

— the distance between the facility and normally occupied buildings;

— actions to be taken in the event of a breach of containment;

— introduction of a “Dial before you dig” policy to minimize the potential for third party interference;

— introducing an area ban on anchor dragging offshore;

— re-identifying a manufacturing facility as a HAZOP zone or similar;

— including a facility or pipeline into the Local Emergency Plan.

Accordingly, where existing infrastructure is to be used, industry participants conduct a thorough evaluation of the conditions and availability of the infrastructure, including appropriate site-specific risk analysis.

6.4.4.2 Examples

The use of existing infrastructure such as natural gas pipelines or offshore oil and gas platforms has been explored for projects in Europe. However, reusing existing redundant infrastructure has proved to be difficult because of issues around timing and the slow progress made on the capture side of the CCS project chain. The safety case that was accepted, for instance, when planning the route for a natural gas pipeline, may not be appropriate were the pipeline is to be switched to CCS CO_2 use. In the UK, the design pressure for bulk gas transfer is lower than that at which the pipeline would need to operate with the CO_2 stream in dense phase, and the design margins (e.g. to inhibit ductile fracture) may be lower. In the US, existing natural gas pipeline infrastructure has been converted in at least one instance to CO_2 transportation and integrated into the CO_2 pipeline network.

7) It is assumed that the original consent to operate such a facility was based on a safety case which included evidence and arguments that demonstrate that the facility was acceptably safe for the specific application and operating conditions proposed.

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6.4.4.3 Conclusions

If existing infrastructure is to be used, conducting a thorough evaluation of the conditions and availability of the infrastructure is recommended to be conducted, including a site-specific risk analysis.

6.4.5 Unintended phase change variations in quality and quantity of the CO_2 stream

6.4.5.1 Context

(OA/XC, C⇆T⇄S)

The impacts of unforeseen variations of quantity or composition of CO_2 streams on the various links of a CCS technology chain can be described as a sequence from source to sink under normal operation conditions. Eventually, in the case of leakage, this sequence could be extended to the overburden, surface waters and the atmosphere (Table 4). Processes leading to variations of CO_2 flux and/or CO_2 stream composition should be considered in the risk management of capture, transportation, and storage, respectively. As any poor performance or interruption of a single link of a CCS chain affects the other links as well, crosscutting risks resulting from the impacts of impurities should be considered for integrated CCS projects.

6.4.5.2 Examples

Unforeseen variations of the CO_2 flux and CO_2 stream composition, beyond tolerable ranges specified in the infrastructure design, can result in the following crosscutting technical risks:

— lower capture efficiency due to inflexibilities in the operation of the upstream plant;

— accidental or intentional interruption or intermittency of the CO_2 stream supply, CO_2 export or transportation;

— CO_2 stream out of specification, or source gas composition not as expected resulting in corrosion of carbon steel components or undermining of the safety case upon which the design is predicated.

In all links of the CCS chain, variations of the quantity and quality of the CO_2 stream can affect the technical performance and reduce capture, transport and injection rates, and hence, the overall quantity of CO_2 emissions avoided. Load variations may result in exceeding or sub-optimal running of designed operational windows, that may result in malfunctioning, venting, or shut downs. Slight changes of the impurities in the CO_2 stream, e.g. the addition of oxygen and injection into oxygen depleted reducing subsurface environments, may have large impacts on geochemical reactions, potentially leading to blockage of pore space in oil reservoirs or saline aquifers, such as by providing the conditions for Sulfate-Reducing Bacteria (SRB) to flourish or by precipitation or dissolution of minerals due to changes in pH or oxidation-reduction conditions.

Further, health, safety and environmental impacts may result from disturbances exceeding the design specifications, e.g. by the release of CO_2 streams containing toxic impurities such as H_2S in CO_2 streams from integrated gasification combined cycle (IGCC) facilities.

This document does not intend to provide a detailed description of the possible effects and consequences of variations in quality and quantity of the CO_2 stream on single components of an integrated CCS project. However, the general consequences of a decreased performance common to capture, transport and storage are considered here. Any effect that reduces the performance of a single process may adversely affect the efficiency of the entire integrated CCS project, resulting in additional costs, more greenhouse gas emissions (e.g. because of necessary blow downs or venting), and/or reduced emission allowances because injection rates and storage capacity are reduced. Eventually, higher wear and corrosion caused by impurities or increased fluxes is likely to cause longer or more frequent maintenance of technical components. Infrastructure that is meant to be durable may need to be replaced, while replacement had not been thought to be necessary at all over the design life. The additional work and unforeseen replacements will result in higher investment and operation costs.

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Secondary, indirect environmental impacts may be caused by disturbances to the designed operation, enlarging the overall environmental footprint of integrated CCS projects. Poor operational performance may increase the energy demand for the CCS chain, and reduce the energy efficiency of power and product generation. The consumption of operating supplies might increase. More waste products and equipment may need to be recycled or disposed. More natural resources may be needed for the disturbed CCS processes compared to the original plans. Ecosystems may be affected by the disposal of capture and process related substances and by the production of an increased amount of operational supplies. Additional greenhouse gases may be released and the overall amount of CO_2 avoided may decrease.

6.4.5.3 Conclusions

Monitoring changes to the CO_2 stream composition and flux along the CCS technology chain is a task of overarching importance to minimize the risks for the overall performance of CCS projects or systems. As in other technological chains, the weakest link determines the overall performance of the chain. Disturbances may affect both upstream and downstream processes. Changes to the purity of the CO_2 stream may be within the limits defined for specific components of the CCS chain, but may result in incompatibilities amongst different impurities once combined. It is a challenge to build and operate CCS projects with a sufficient and equal strength of all its stages, aspects, and links. Weak links cause disturbances and increase overall costs. Surplus measures, such as design redundancy for critical systems may be included to ensure optimum performance of one link amongst others of mediocre performance will increase costs as well, without significantly improving the overall performance.

Crosscutting risks may result from liabilities for technical components and processes that might adversely affect others. Boundaries of technical units may not always coincide with responsibilities for operation or warranty. If financial provisions have not been made for unexpected maintenance and replacements, equipment may be used at its technical limits and eventually beyond. Risks of larger failures and cascading consequences may rise if necessary maintenance of technical components or monitoring of the injection process are postponed.

6.4.6 CO_2 out of specifications/Source gas composition not as expected

6.4.6.1 Context

(XC, C⇆T⇄S)

Various features, events and processes have the potential to affect the composition of the CO_2 stream during its flow through the links of a CCS chain. Impurities interact physically and chemically with their surrounding environment to an extent that may be technically relevant (see Table 4). These interactions result in processes, which may have a negative impact on the local environment and CCS-projects performance or infrastructure in general (Rütters et al., 2015).

6.4.6.2 Examples

Source: Impurities in the CO_2 stream originate from the CO_2 generation, either in heat or power generation or in industrial processes. Primarily, the spectrum of impurities and their concentrations are related to the process by which the CO_2 has been produced or extracted, and the quality of the original carboniferous materials used. The production processes may include cleaning of the gas streams, e.g. flue gas filtration or desulfurization, which might impact the composition of the CO_2 stream. Changes to the production process or to legal requirements may further change the composition of the gas stream entering the capture facility.

Capture: Carbon dioxide can be captured by various technologies, such as solvent scrubbing, oxyfuel combustion, and solvent wash (as in IGCC). The capture process can be an integrated part of power generation or industrial processes. It can include cleaning and compression of CO_2 streams. For such integrated facilities various standards may apply to the technical components. The concentrations of impurities in the CO_2 stream are affected by many capture-process dependent factors, such as solvent quality and regeneration, air separation, water removal, flue gas cleaning (e.g. denox or desulfurization),

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variations in flux rates, or regulatory requirements. Negative impacts resulting from impurities may include among others: enhanced degradation of solvents, corrosion, foaming within pipes and vessels, and clogging of adsorber and desorber columns, wear of turbo-machinery by abrasion caused by droplets of condensate or ash. These impacts may result in reduced capture rates, interruptions of the capture process and eventually venting of process gases or CO_2 streams.

Transportation: Changes to the spectrum of impurities during transport could result from mixing of different CO_2 streams in pipeline networks, especially by those that are derived from different sources and capture technologies. Even if individual concentrations of impurities are below technically tolerable thresholds some impurities may not be compatible with each other. Some combinations of impurities may trigger chemical reactions affecting the transport properties of the CO_2 stream and the transport system. Water, SO_2 and O_2, for example, can react to form sulfuric acid, enhancing steel corrosion. Minor changes in CO_2 stream composition may occur because of condensation or reaction with the wall materials of pipelines or vessels. Other ISO standards such as ISO 27913 address this issue.

Injection: During interrupted injection, formation fluid may enter the well and contact the CO_2 stream causing changes to its composition because of partitioning of substances between the aqueous and CO_2 phase. During continuous injection, little change to the composition of the CO_2 stream is expected within wells, as the time for reactions with steel surfaces is small compared to the time the CO_2 stream is in contact with steel pipes or vessels. However, transport in high quality steel pipes to former production wells in depleted hydrocarbon fields, made of plain carbon steel[8)], are likely to be problematic. Equally, combining pipes of different quality in CCS systems may result in joins that could possibly be sensitive to corrosion reactions: these should be subject to appropriate monitoring and risk treatment.

Storage: Major changes to the compositional spectrum of impurities are expected in the storage reservoirs, where the CO_2 stream including any associated impurities may mix with residual gas in depleted gas fields or react with oil, coal, formation water and minerals. Mixing of CO_2 streams with residual gas changes its density and the CO_2 content in the resultant stream and thus impact storage capacity (Rebscher and Oldenburg, 2005; Schöneich et al., 2007). Effects of mineral reactions with the injected CO_2 stream may result in the dissolution of primary minerals or the alteration of the rocks and the formation of new minerals. The chemical reactions caused by CO_2 and impurities may be effective at different sites within a storage and change with time. As a result of these reactions, pore spaces and pore connectivity may be enlarged or reduced and hence the permeability of the reservoir or caprocks. Depending on whether reservoir or cap rocks are affected and depending on the time scale of the geochemical reactions, the resulting consequences may be beneficial or detrimental to the storage purpose. Self-sealing of fractures in the cap rock or well bore cement, and mineral trapping of CO_2 are positive effects of mineral precipitation. Mineral dissolution of carbonates, enhanced by sulfuric or nitrous acid, may create an improvement in the permeability of reservoir rocks. However, dissolution reactions involving CO_2 streams and associated impurities may adversely affect the quality of the cap rock, while extensive mineral precipitation within the reservoir could reduce CO_2 stream injectivity. In addition to mineral reactions, impurities may lead to changes in fluid parameters such as density and viscosity of both the CO_2 stream phase and formation fluids, affecting transport properties. Necessary injection pressures may change, when the composition of the CO_2 stream changes within the reservoir.

Leakage: ln the case of leakage, impurities entrained in fluids leaving the storage reservoir could interact with surrounding materials, including environments that are natural or manmade (boreholes or abandoned wells). As in the reservoir, reactions could take place in the overburden, changing the composition and the properties of the CO_2 stream. The resulting effects may be positive or negative: corrosion of metal-based materials and cements may enhance pathways, while other reactions could result in the self-sealing of fluid pathways. The CO_2 stream may physically mix with formation waters, rising together though pipes or faults (gas-lift). Leakage from the reservoir into overlying, deep secondary or reserve storage formations, may be acceptable, if these formations do not host economic resources such as hydrocarbons. Impacts on freshwater aquifers, which are current, or potential future drinking water resources, and on soils suitable for food production are of particular concern. Human

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8) Plain-carbon steel, is a combination of two elements, iron and carbon, with other elements present in quantities too small to affect its properties. The only other elements allowed in plain-carbon steel are: manganese (1,65 % max), silicon (0,60 % max), and copper (0,60 % max).

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health and safety, protected ecosystems, and private property are, of course, also elements of concern that are usually the focus of risk management.

6.4.6.3 Conclusions

Some impurities may have beneficial effects in some parts of the CCS chain, thus it may be acceptable not to take measures to reduce their concentrations. In other parts of the chain however, these impurities may have negative effects. For example, the presence of SO_2 may enhance injectivity and storage capacity for the CO_2 stream but is likely to also accelerate reaction rates and to facilitate reactions not possible in its absence, enhancing corrosion of the transport and injection infrastructure (Ziabakhsh-Ganji and Kooi, 2014). There may be a competition between economic arguments and risk management in defining the tolerable level of impurities. From a risk perspective, As Low As Reasonably Possible (ALARP) may be a desirable criterion, while economists may try to find the minimum of costs resulting from purification of the CO_2 stream and damage caused by impurities, balancing costs and benefits (Brown et al., 2014; Eickhoff et al., 2014), e.g. from enhanced hydrocarbon recovery (Besua, 2010).

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Table 4 — Overview scheme for risks related to impurities in a CCS chain

	Pre processing	Capture and Compression	Transport	Injection	Storage	Leakage
FEPs to be considered	— combustion facilities — industrial processes	— solvent scrubbing — oxy-fuel — IGCC solid chemical looping	— pipeline — vessel	— well	— saline aquifer — depleted gas field — depleted oil field	— (abandoned wells) — overburden — freshwater aquifers — soil — sea and freshwater
Cause affecting CO_2 stream composition	— process interruption — changes in: — fuel or raw material quality — combustion or production process — regulatory requirements — flux rate variations	— solvent quality — solvent regeneration — capture rate variations — gas cleaning — drying — compression steps, — regulatory requirements	— mixing of different CO_2 streams — residual gas in vessels — reactions with wall material	— reactions with wall material	— reactions between — CO_2 stream, water, gas, oil, coal, minerals	— mixing of fluids — reactions between CO_2 stream, well material, overburden, groundwater, soil, surface-water, atmosphere
Effects **(examples)**		— solvent degradation — corrosion — foaming — clogging — abrasion by droplets and ash, — phase mixtures in installations designed for single-phase operation	— mixed incompatible streams — reactions causing — clogging — corrosion — condensation	— corrosion — two-phase flow — cement stability	— CO_2 phase dilution — density reduction — precipitation — dissolution — hydrate formation — enhanced geochemical reactions	— well corrosion — pH reduction — mixing of formation and ground water — physiological effects — freshwater contamination
Specific risks		— reduced capture — capture interruption — venting of CO_2 stream	— reduced transport capacity — transport interruption — leakage to atmosphere — HSE	— reduced injectivity — injection stop — leakage to atmosphere, subsurface, ecosystems — HSE	— reduced injectivity — reduced capacity — project interruption — HSE — project failure	— enhancing leakage pathways — groundwater contamination — impact on soil and surface ecosystems — leakage to atmosphere — HSE impacts

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Table 4 *(continued)*

	Pre processing	Capture and Compression	Transport	Injection	Storage	Leakage
General risks associated with specific risks		— more maintenance resulting in additional costs — lower injection rates and/or storage capacity — uncovered liability for cascading and progressive effects — technical boundaries may not coincide with management responsibilities — rendering of emission certificates				

6.4.7 Mismatched component performance

6.4.7.1 Context

(XC, C⇆T⇄S)

A CCS project involves multiple complex processes, including CO_2 capture, transportation, and storage. A project may comprise a single source-sink combination or an extensive CCS infrastructure containing multiple sources and sinks. It is also a long-term dynamic system to which components might be added or removed components as needed. Performance of individual components such as the storage reservoir (volumetric capacity or injectivity), engineered infrastructure (flexibility, operation hours), and remaining life of any component may be mismatched in the system, which might limit the performance of the integrated CCS system.

6.4.7.2 Examples

Example: Boundary Dam – Aquistore (temporary shortfall in CO_2 delivery; financial impacts and challenges in plume monitoring.

At the Boundary Dam coal-fired power station in southernmost Saskatchewan, Canada, one of the generating units was retrofitted for CO_2 capture. The CO_2 captured from Boundary Dam is used primarily for EOR at the Weyburn Unit oilfield, supplementing CO_2 that has for years been transported by pipeline directly to the oilfield from the Dakota Gasification Company (DGC) synfuels plant in North Dakota, USA. CO_2 from Boundary Dam that exceeds the oilfield operator’s needs is provided to Cenovus (the Aquistore CO_2 saline storage project). During the commissioning period of the CO_2 capture unit, service interruptions on the power-plant side caused shortfalls in the expected CO_2 delivery to the oilfield, which in turn limited the CO_2 supply to Aquistore. Because the CO_2 capture plant temporarily operated at less than half the design capacity, revenue from expected CO_2 sales was lost to Boundary Dam’s owner SaskPower, which also paid penalties to the oilfield operator. In this case, the lesser performance the CO_2 capture stage imposed financial impact of failure to deliver CO_2. This impact might have become important to the CCS project if performance had not improved.

At the Aquistore CO_2 storage project, the prospect of limited CO_2 delivery raised concerns among project scientists that the effects of the smaller injected mass of CO_2 might not be detectable through the designed monitoring scheme. If this had occurred, it would have implied the loss of research investments (in baseline monitoring, equipment purchases, and design effort) and ultimate research value. The implications of these start-up-period shortfalls highlighted risks that, had the situation remained unchanged, could have been significant to further plant and CCS project operations. As of May 2016, the retrofitted power unit and CO_2 capture unit had been running smoothly at near-capacity levels for several months.

The Jilin CO_2-EOR project completed the construction of a 0,5 million tonnes per annum (Mtpa) injection scale project, but an insufficient CO_2 source resulted in an actual operation scale of 0,28 Mtpa. Therefore, the facilities are not working as effectively as planned.

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At the In Salah project, the injection rate of CO_2 in mid-2010 was reduced and the injection stopped in June of 2011 as a safety measure, due to preliminary conclusions regarding the reservoir properties (mainly related to capacity) (Statoil, 2013a).

At the Snøhvit project, CO_2 injection into the Tubåen Formation started in April 2008, and continued until April 2011. During this period, the injection was occasionally halted due to operational challenges at the LNG plant that provides the CO_2 stream. The injected volume was less than planned; nevertheless, the pressure built up faster than expected. After an intervention into the injection well, the shallower Stø formation was perforated at the new CO_2 storage formation in April 2011(Norwegian Petroleum Directorate, 2013; Statoil, 2013b). The injected volume was less than expected. By 01/01/2015t over 1 million tonnes CO_2 had been injected into the Tubåen Formation, 1,8 million tonnes into the Stø Formation, and over 1/2 million tonnes CO_2 had been vented (Moumets et al., 2015). A new injector well is being planned to make the CO_2 injection as robust as possible.

6.4.7.3 Conclusions

The practical capacity of a single source-sink combination at a certain time is determined by the lowermost value of the practical capacities of the three CCS primary components (capture, transport and storage). Underperformance of any one of the three components can lead to underperformance of the other two.

For a single source-sink combination, the total amount of the stored CO_2 in the project lifetime, ignoring CO_2 loss during the operation, is determined by the practical capacity and the life of components.

When there are no incident-induced interruptions or intermittency, uncertainty arises, primarily from the operation hours of capture component, and the injectivity of the storage component.

For an extended CCS infrastructure with multiple capture components and storage components, if the capacity of transport components is sufficiently large and stable, the amount of the CO_2 stored for the system in its lifetime is ultimately determined by the practical capacity and the life of components.

Another factor affecting the uncertainty of the integrated CCS system is the remaining life of the storage component which is basically affected by injectivity and storage resource characteristics.

Remaining life mismatching leads to a decrease of the CO_2 storage volume of the integrated system, such as happened at In Salah.

6.4.7.4 Risk identification and analysis

As stated above, the mismatching of systems may occur in the whole system and normally in the operational phase. The factors influencing mismatching can be characterized as follows:

— The number of operation hours of plant operation

  The number of operation hours in the example of a power plant follows an electricity market demand trend. Peak shaving, maintenance, or interruptions of the power plant may all affect the operation of the capture component, leading to CO_2 supply fluctuation in the system.

— The injectivity of the storage component

  Injectivity may be higher or lower than expected due to various factors. With continuous injectivity activity, there may be a loss of injectivity due to (1) pressure build-up, (2) operational upsets, (3) well interventions, (4) dropping BHP (Bottom Hole Pressure) constraints, or (5) geochemical alteration of the reservoir, e.g. halite precipitation (Groot, 2011).

— Storage resource

  Information about this factor is presented in “insufficient storage resources” (see 5.4.9).

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6.4.7.5 Risk treatment

Measures in response to the mismatching within a CCS system include flexible operation and multiple CO_2 sources, and a contract or guarantee to have sufficient CO_2 in the system among the operating plants and networking components.

— The number of operation hours of plant operation

Multiple capture components (for example, multiple compressors in a power plant or sources from multiple plants) may be needed to adjust the mismatch of system. In addition, the CO_2 in the system should be first guaranteed in the operation of plants. More information about flexibility operation is presented in “Lower capture efficiency due to the upstream plant flexible operation” (see 6.4.8).

— The injectivity of the storage component

Plans to increase perforations, fracture the geological storage formation, or bring online more wells to meet injection capacity may be needed in advance.

— Storage resource

Solutions to expand the storage resource should be reserved, such as choosing a new storage site, as happened in the Snøhvit Project. More information about the injectivity and resource of the storage component is presented in “Insufficient storage resource” (see 6.4.9) and “Reservoir does not perform as predicted” (see 6.4.10).

6.4.8 Lower capture efficiency due to the upstream plant flexible operation

6.4.8.1 Context

(XC, C→T→S)

The planning of CCS infrastructure and investment decisions can bind capital for decades, hindering the introduction of new technology to accommodate rapid changes in markets. Such changes are accelerated by politics fostering CO_2 emission reduction by means other than CCS, such as a transition toward renewable energies. Markets for energy, power, and industrial products have become larger (global) and less predictable. Therefore, industries using fossil fuels tend to prefer plants facilitating flexible operations, changing shares of output between energy, electrical power, or chemical products. Further, some plants have significant fuel flexibility. Cement kilns are one example of very flexible firing sites, as the high temperatures in the kilns allows a broad range of combustible materials to be used.

6.4.8.2 Examples

Prominent examples for this XC risk in the energy/power generation area are:

— combined heat and power plants;

— IGCC power plants;

— co-firing of waste or biomass of variable composition and water content.

Including such plants into CCS systems, especially in simple systems, requires decisions in advance of which business or operation should be given preference in the operation, either CO_2 source related processes or CO_2 storage. As a result, the technical infrastructure may be designed differently. This decision may not only take into account economic considerations but should also include technical limits of capture, transportation and injection flexibility.

Combined heat and power plants may switch on a seasonal basis between heat supply to district heating networks or using heat for an efficient power generation process. When heat is delivered for district heating, it cannot be used for drying of fuel, such as lignite or biomass. This will result in changes of water content within the flue gas and should match with an adequate flexibility in the gas drying facilities.

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Conventionally, large base load power plants fired by coal are designed for a relatively narrow optimal range of fuel composition. Thus the flue gas flux and composition should be relatively constant. However, because of more variable power markets that should integrate larger shares of renewable power, a more flexible mode of operation is now the practice for some of these power plants. Short-term load changes within less than one hour result in fluctuations in gas fluxes and possibly in flue gas composition during switching the boiler firing which may affect the composition of the CO_2 stream.

6.4.8.3 Conclusions

The variability of processes in chemical industries is process, raw material and product dependant. CO_2 streams might also be used for CCU options such as CO_2-EOR, as an alternative to storage. Because of the many possible scenarios, a further differentiation of CO_2 sources from chemical industries is not possible here.

6.4.9 Insufficient storage resource

(XC, S→T→C)

6.4.9.1 Context

Although an insufficient storage resource concerns storage specifically, it may impact the whole value chain, as far as it stops capture and transport and the corrective measures are not immediate. This risk is tightly linked to risk 6.4.10, i.e. reservoir does not perform as predicted (injectivity reduction, storage resource, geomechanical stability, containment), and 6.4.11, i.e. model uncertainties regarding storage performance (capacity, injectivity, containment). Nevertheless, this risk concerns the reservoir capacities as a whole.

6.4.9.2 Examples

Insufficient storage resource might be detected first during the injection tests of the construction phase and then during the operational phase.

<u>Pre-operational phase</u>

The principal parameters to be checked during the injection tests are the permeability and the injectivity of the storage formation. Containment of the injected CO_2 in the reservoir is also crucial to ensure storage capacity. This requires low permeability of the caprock and lack of any leakage pathway (e.g. unexpected fault, abandoned well). Abnormal high values of injectivity during the tests could be an indication of insufficient containment. Two possible scenarios of evolution are possible: either limited storage capacity, which means unconformity with performance predictions or migration of the CO_2 plume towards a zone of inadequate containment and possible leakage out of the storage complex. Possible consequences on the CCS value chain are to delay or stop of the capture plant construction and/or need to change or extend the pipeline route.

<u>Operational phase</u>

As for the pre-operational phase, insufficient storage resource can be due to

a) low permeability or low injectivity of the storage formation,

b) extension of the storage formation less than forecast due to geological uncertainty, and

c) unexpected leakage pathways, e.g. fault or high permeability of the caprock.

Unconformity of the storage predicted performances can stop injection and consequently transport and even capture. In case of lack of any alternative solution to storage, CO_2 could be emitted to the atmosphere at the capture site. In that case, the CO_2 emitter may incur financial cost if emission certificates need to be bought or cannot be traded.

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6.4.9.3 Conclusion

Storage site screening and characterization phases are intended to discard any site with insufficient storage capacity. Nevertheless, this risk should be taken into account in the global risk management plan, since the consequences are high for the whole project, particularly because a project could be delayed for years, waiting for a new storage site.

— Risk treatment during the pre-operational phase

  The insufficient storage resource risk at the pre operational stage can be treated either by testing another formation at the same site, using the same well or drilling a new one from the same platform or close by, or by searching for a new storage site close to the initial one, keeping the same transport pipeline. A more drastic solution could be using another storage site, even one already existing, which implies changing the pipeline route. In both cases additional characterization studies and injectivity tests are needed.

— Risk treatment during the operational phase

  If the capacity of the targeted reservoir appears to be insufficient during the operational phase, it is necessary to find rapidly a replacement storage site. As for the pre-operational phase, there are mainly three options:

  1) try another overlying or underlying formation;

  2) search for a new storage site in the vicinity or last;

  3) find a new storage site in a different area and provide a new pipeline or another transport route (e.g. by ship).

  In the meantime, it will be necessary to find a temporary storage site for the captured CO_2.

  To prevent this kind of risk, it would be worthwhile for the regulators to ask the operator to include enough overdesign to reduce this risk to an acceptable level or to include this risk in their risk management plan, proposing alternative storage sites in case of insufficient storage capacity for the selected one.

6.4.10 Reservoir not performing as predicted

(XC, S→T→C)

A reservoir might not perform as predicted due to lower than expected CO_2 storage capacity in the reservoir due to properties being found to be worse than expected, e.g. lower than expected reservoir thickness, poor porosity, the unexpected presence of natural gas (methane), or rock compressibility. Gradual build-up of reservoir pressure may cause the eventual loss of storage capacity due to the maximum pressure constraint being reached. Pressure build up may be alleviated by increasing well numbers and by pipeline extensions to create larger inter-well spacing, to access pore space elsewhere within the storage formation.

Poor lateral connectivity within the storage formation results in insufficient connected storage volume due to compartmentalization and the presence of pressure boundaries (associated with fault zones or facies boundaries). Gradual build-up of reservoir pressure can cause the eventual loss of connected storage capacity due to the maximum pressure constraint being reached.

CO_2 migration along a fault pathway can take place through the existence of permeable fault systems that act as conduits to shallow strata.

Low injectivity can be experienced due to poorer than expected near well bore properties (permeability, skin effect). In this case, the reservoir permeability or thickness is discovered to be below the expected range of uncertainty based on all available data or the skin is higher than anticipated, either of which can lead to an increased cost (more wells) and potentially more time required to meet sustained injection at the contractual injection capacity.

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6.4.11 Model uncertainties regarding the storage performance

(XC, S→T→C)

6.4.11.1 Context

Subsurface data and geosciences modelling have direct influence on predicting the capacity, injectivity and integrity of the reservoir, the performance of which can affect the whole CCS chain, as the reservoir is the receptacle and the ultimate sink of the CO_2 streams. The reservoir performance is a key parameter of the whole CCS chain and influences the level of flexibility necessary for each of the CCS elements.

The level of confidence in the reservoir performance has an influence on the start-up phases of the project, on the design choices of the surface installations, the necessity of buffer storages, of interconnection between storage sites, of producing water wells, and the number of injecting wells. Before and during operation, the confidence in this prediction is re-assessed. If subsequent observations using monitoring techniques are not within the range of the model predictions, the storage operation may be suspended for an undefined period while the anomalies are investigated. This would have consequences on the whole CCS chain. Injectivity losses may require lowering the injection flow rate and additional measures to avoid this may be necessary on existing wells or even new wells.

Quantifying and managing these uncertainties from start-up phase to operational phases are of importance to ensure global performance of a CCS project. Monitoring data used for long-term behaviour of the storage complex will also be used to re-evaluate the accuracy of existing models.

Most of the methods and tools employed to quantify uncertainties related to a CO_2 geological storage, despite the specific size and long-term performance expected of this kind of storage, are developed and used by current industrial activities dealing with underground data (coal mining and the oil and gas industry).

Models are used all along the storage characterization process, at various scales (basin, reservoir, micro and nano-scales) and involve various disciplines: geology (sedimentology, depositional processes, stratigraphy, structural), geophysics, geomechanics, geochemistry, petrophysics, reservoir engineering.

Several geostatistical methods can be used to simulate nature, geological parameters heterogeneity, to couple different models and to quantify uncertainties while keeping consistency with real geological, geophysical, test and production data.

6.4.11.2 Examples

Uncertainties in geosciences models may be a result of:

— Input data uncertainties depending on the level of details of the knowledge of the storage complex characteristics: geological data, geochemical, geophysical, flow parameters. Geophysical acquisition, processing (time-depth conversion), joint inversion with cross check from different sets of geophysical measurements (electromagnetic, seismic, gravimetric) and their interpretation are also sources of uncertainty. Geochemical characteristics of the reservoir and the caprock, flow and petrophysical parameters, geomechanical stress regimes, their spatial variability (continuous and/or discrete evolution) have direct influence on the long-term integrity of storage, the level of risks and the scenarios to consider. The data themselves, when existing are often sparse, some of them are extrapolated from lab experiments (such as core-flood measurements) or from analogues.

— The choice of models and their parameters, the assumptions made of predominant physical and chemical factors, the coupling of several models, the size of mesh, the modelling methods taking into account discrete elements such as fractures.

— The optimization of computing, sometimes requiring simplification, adding some uncertainties on results.

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These uncertainties have influence on CO_2 stream storage volume estimations, injectivity of the reservoir, CO_2 plume extension, as well as on long-term performance of the storage:

— CO_2 stream storage volume estimations and injectivity

  — Efficiency coefficient whose value can show important variations through time depending various assumptions and can change the global storage volume estimations by one or even several orders of magnitude (IEA GHG, 2014).

  — Lateral and vertical heterogeneities have crucial influence on CO_2 migration, dissolution and on pressure perturbation and propagation, thus modifying the constraint fields in the reservoir. The mesh size, the choice of the model and of the numerical scheme are of particular importance to model these effects properly.

  — Thin intra-reservoir shale layers have high influence on fluid flows and capacity estimation. This has been shown in several feedback reports from injection at real fields, such as Snøhvit, Sleipner, K12B and In Salah as well as in studies like the Paris Basin (Bouquet et al., 2013).

  — Safe injection is crucial. Geomechanical modelling (Ryerson et al., 2011) develops an understanding of the geomechanical effects such as fracturing and induced seismicity.

  — Geochemical conditions in the injection well vicinity, as well as further in the reservoir, can have a strong influence. An example of this would be salt precipitation which inhibits injectivity (Snovhit).

  — It is also necessary to reduce the model uncertainties with inputs from natural analogues, generic laboratory works, but also specific field tests and core measurements (prior to and after CO_2 stream injection).

— CO_2 plume extension, CO_2 stream storage long-term integrity

Usually geostatistical distribution will be designed for each parameter to cope with lack of data and to calculate a probabilistic response for the storage performance parameters, like CO_2 reaching a specific concentration at a specific area (Zhang et al., 2009).

As an example, to predict the CO_2 plume extension, the IRS (Independent Random Set) method can be used to combine both aleatory and epistemic uncertainties. While some model parameters can be handled within a classical probability framework, due to the availability of data, other parameters are dealt with using possibility theory, due to the imprecise or incomplete nature of the available information. Results of calculated CO_2 plume extension are presented in terms of distributions of the upper and lower probability that plume migration distance lies below a certain value. In a decision-making framework, these results could be combined into a single distribution, referred to here as a “confidence index”, such as a weighted average of upper (optimistic) and lower (pessimistic) probabilities that migration distance is below a certain value. The selected weight reflects the decision-maker's degree of “risk aversion”. This method allows the determination of the range of probability of an event such as the presence of a specific concentration of the CO_2 stream in a specific zone, thus feeding the risk assessment of the storage system (Bellenfant et al., 2009).

Geostatistical methodologies are also used to assess the CO_2 storage according to DNV guidelines (Det Norske Veritas, 2009):

— Estimate the effective resolution of the simulation models used. Multiple simulations should be performed based on different geostatistical realizations of the geology in order to allow estimation of variability of the key output parameters. The resolution of the simulation models should ideally be designed to reflect the reliability of the data and be consistent with the resolution of the geological model.

— Adapt the models to the observed reservoir behaviour, during the operational phase. The uncertainty associated with the geological model should be assessed. Emphasis should be put on assessing uncertainty related to features and parameters that have an impact on capacity and containment characteristics, as well as parameters that may have a strong influence on the subsequent reliability

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of modelling and forward predictions. When assessing the uncertainty span, propose to identify and evaluate best-case and worst-case scenarios with regards to capacity, injectivity and containment, as well as the potential for monitoring and verification. It should also be indicated what efforts will be made during operations to reduce uncertainty in the geological model further by calibrating parameters with observations.

Sensitivity analysis and history matching techniques are of great help to reduce the uncertainties in the model. An example of sensitivity analysis in geochemical modelling would be that of its impact on the geochemical and reaction pathway modelling. Addressing thermodynamic database uncertainty and uncertainty due to the selection of secondary minerals can help refine the amount of CO_2 stored by mineral trapping (Dethlefsen et al., 2012).

History matching and other dynamic model update methodologies are used to validate risk assessments and compare predicted with actual performance:

New input data can be collected from the operation data. It can be dynamic data related to fluid flow such as a hydraulic head (or pressure) measurement or other monitoring data such as repeated seismic acquisition.

History matching techniques may be used to refine not only the reservoir model but also the geological model, to keep consistency with physical, chemical properties and geological deposit processes history, as far as the new data collected can be inverted and converted to input data and give valuable new information and accuracy.

History matching seismic impedances from 3D reservoir fluid flow and petro-elastic simulations can be compared with those obtained by 4D (time-lapse) seismic inversion. The objective is to build predictive flow models directly constrained by the geological (borehole) and geophysical (seismic) information.

6.4.11.3 Conclusions

Each storage site being specific, physical, chemical and biological phenomenon at both micro and macro scales should be taken into account before elaborating statistic models.

Coping with lack of data or sparse spatial and temporal data, managing change of scales, optimizing computing and assessing the probabilities associated with the model's outputs while keeping model consistency with reality are the challenges that can be addressed by geostatistical methods. Together with most accurate physical and chemical modelling as well as a wise choice of technical solutions, these methods help define worst and best case scenarios and quantify the model's uncertainties and outputs distributions.

Model uncertainties can strongly influence the development of the whole CCS system. Their quantification through various efficient and proved geostatistical methodologies, together with good geological knowledge and the engineering of technological barriers that limit the effects of undesired events, dramatically reduce the risk of unexpected downgraded performance. Combined and refined with observations data, the methodologies used allow operators to define an envelope of predicted safe and effective behaviour of the system. Improvements are needed to better predict the long-term behaviour and safety of storage sites to enable post-closure stewardship.

6.4.12 Lack of maintenance and emergency control procedures/safety-related accidents

6.4.12.1 Context

(XC, C⇆T⇄S)

The CCS process requires continuing three major operations simultaneously: capturing CO_2, transporting CO_2 and injecting CO_2 into reservoirs. Daily continued operation requires a CCS process to carry out the same risk management procedures as any other specific industrial systems and processes. If an inadequate risk management exercise were to occur, it could lead to a lack of maintenance and/or emergency control procedures. Then there is a chance that errors, incidents, or in the worst-case, safety related accidents could occur. Lack of maintenance and/or lack of emergency control procedure are

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potential causes of a safety incident. Once a potential risk takes effect and stops any single element of the CO_2 capture system, transportation system, or injection system, the whole CCS process is likely to stop operating.

6.4.12.2 Examples

While the number of CCS projects worldwide is too small for a statistically relevant database for risk analysis and risk management based on CCS projects alone, an immense quantity of records and statistics are available from similar industries, which could be pooled to characterize risk scenarios and to estimate likelihood and uncertainty.

The example is given for a CCS system, which handles 10 000 tonnes of CO_2 annually (Tanaka et al., 2013). Statistics from the Japanese gas industries for example, indicate that an uncontrolled escape incidence of CO_2 is likely to be 0,5 to 0,2 times per year per 10 000 tonnes annually produced. The same rate might be extrapolated to apply to CCS applications. In most cases, across the sites included in the statistical population, the level of impact was assessed as “very slight” or less. In just one event within the above sample, an incident took place which propagated to an explosion leading to physical impacts to people and property on the site and/or in the vicinity. This event was a result of a combination of poor emergency preparedness and bad operational procedures.

Two examples of non-CCS CO_2 related accident cases, experienced by in ground surface industries, when risk management went wrong and maintenance and/or emergency control procedures were poor are as follows:

— An accident resulting from human errors during repair work (CO_2 gas storage tank, Fukushima, Japan, 1969) (Brown, 2010a). The tank had been isolated in preparation for repair work. The power supply to the refrigerator stopped but the power supply to the tank heater remained on. The liquid carbon dioxide present in the tank, combined with the continued heating, caused the temperature and pressure of the carbon dioxide in the tank to rise until the burst pressure of the tank was exceeded, and a crack was generated in the tank wall. The tank pressure then equalised with the atmospheric pressure via the crack but this rapid drop in pressure meant that the liquid CO_2 within the vessel generated a vapour explosion, causing tank rupture. Debris from the rupture was scattered up to 60 m away and a slate-roofed factory within a 50 m radius was completely destroyed. Windows of houses located within a 500 m radius were reported to be also damaged. Three people were killed and 38 injured.

— An accident led by lack of emergency preparedness (a research institute, Idaho, USA, 1998) (Brown, 2010a). A high pressure CO_2 fire suppression system was unintentionally discharged in a laboratory. They had not installed a CO_2 concentration detector or an alarm system, or escape route lighting, or provided emergency breathing apparatus. Because of budget restraints, no emergency evacuation drills had been practised. One person died and several workers sustained life threatening injuries.

The triggers and causes of these two CO_2-related accident cases in adjacent industrial areas are typical in the context of a safety-related accident. In the first case, the explosion was initially triggered by poor-preparations for the repair work. The preventative measure would be clear manual preparation for repair work based on risk analysis and assessment and the application of a robust Permit-to-Work system that ensured that safe working practices (e.g. isolating electrical supplies before maintenance work commences) were in place. In the second case, an unintentional CO_2 gas release led to a fatal accident. Lack of emergency awareness and preparedness exacerbated what should have been a routine escape response. Proactive risk assessment and risk management would have prevented the fatal accident.

In the oil and gas industry, incidents typically result from causes such as improper well drilling and maintenance, age deterioration of materials, or corrosion of metals and degradation of cement. These can cause what starts as very slow release of gas to suddenly release a large volume of gas or liquid, a phenomenon called “blowout”. The USA has comprehensive accident databases of well works incidents. Analysis of the statistics suggests that the incidence of blowouts in a well could be estimated as approximately 0,005 times per well (Celia et al., 2009; Celia et al., 2011; J.P.Nicot, 2012).

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A blowout accident case took place in Hungary, and provides some idea of what happens when maintenance and/or emergency control procedures go wrong in well operations:

— An accident caused by an unintentional incident happened during regular well maintenance [EOR, Nagylengyel, Hungary, 1998(Brown, 2010a)]. The incident took place on a CO_2 collection well. Routine work was put in hand to replace a blowout preventer with a Christmas Tree well-head completion, and during this the operators tried to disengage the quick-release packer (−202 m) from the production pipe so that the pipe string could be lifted up. Instead of the quick-release coupler being released, it is likely that they dislodged the packer seal at −2,175 m, providing a passage for carbon dioxide gas to escape through the annulus between the 27/8” (73 mm) production pipe and the 65/8” (168 mm) conductor casing. When the operators disconnected the blowout preventer, carbon dioxide gas started to leak out, so they tried to replace the blowout preventer and retighten the mounting bolts. However, they had only inserted two when the carbon dioxide blowout started with the full force of 207 bar. CO_2 started to escape and 5 000 residents in the immediate area were evacuated.

  In this case, emergency preparedness based on risk assessment would reduce the consequences.

In other cases of well of blowouts in the oil and gas industry, there have been lower impacts on people living in the vicinity. When the well pressure is high, it can lead to a blowout of gas and liquid from the reservoir including some H_2S and CO_2 in the oil or gas. This can last for a few hours or days. When it lasts for longer periods, to avoid adverse impacts a precautionary evacuation of nearby residents may be necessary. Nevertheless, the pressure of a CCS reservoir may be smaller than oil or gas producing reservoirs, particularly where the CO_2 stream is being stored in a depleted natural gas or oil reservoir. In many cases, the risks and impacts of blowouts from a CCS processes could possibly be estimated to be smaller than that of the oil and gas industry.

6.4.12.3 Conclusions

To prevent any safety related accident, risks of lack of maintenance and/or lack of emergency control procedures should be analysed thoroughly and managed according to ISO 31000 and relevant risk assessment techniques. In identifying risks arising from a lack of maintenance and/or lack of emergency response provisions in CCS procedures, operators can refer to experiences of risk identification from the conventional chemical plant industry, gas transportation and the mining industries. The extent to which parallels can be drawn is limited by the specific nature of the CO_2 stream (and the volumes involved), for which there is no exact equivalent, either for its production or its transportation. As a result, risk assessments should also include the results of any accident enquiries and any research into relevant failure mechanisms, such as corrosion or leakage, so that appropriate risk scenarios can be developed.

A risk identification document should therefore be prepared to mitigate against an accident as a result of a lack of maintenance and/or lack of emergency control. Such a document would be expected to include:

— a description of the potential risks of CO_2 in relation with capture, transportation, and storage;

— an analysis of incident and/or accident cases and statistics from relevant industries;

— technical recommendations;

— reference to relevant technical, environmental, or operational standards (international and/or local);

— a list and summary of relevant national or local legislative requirements.

Once the sources of risk, areas of impacts, events (including changes in circumstances) and their causes and their potential consequences have been identified, the risk assessment process can follow. An effective risk control strategy avoids any potential risks that significantly affect CCS operations.

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6.4.13 Corrosion and material problems

Context

(XC, C⇆T⇄S)

CO_2 is non-flammable. But carbon dioxide can lead to corrosion when water is present, so water content control, monitoring and management of the internal corrosion are necessary (de Visser et al., 2007)[9]. Besides water, corrosion depends very much on the concentration of impurities contained in the CO_2 stream, e.g. O_2, SOx and NOx can enhance corrosion in wet CO_2 streams. In addition, in the event of a significant leak, CO_2 may concentrate close to ground level because its specific gravity is higher than air, increasing the chance of inhalation by animals in the vicinity (compared to, for instance, natural gas which is lighter than air and rises to disperse rapidly in the atmosphere).

CO_2 does not have a high degree of toxicity, but it displays symptoms at one level or another almost as soon as it is absorbed. Serious symptoms might be experienced to inhabitants local to a large leak from the CO_2 stream without them noticing, because CO_2 on its own is without taste or odour. If there is H_2S in the CO_2 stream, the unpleasant odour of bad eggs would serve to alert people that there is a problem, and their inclination would be to find an area away from the smell until it had dispersed.

If leakage caused by corrosion occurs within any of the CCS processes, there is the risk that the integrity of the whole system is undermined. Crosscutting risks resulting from corrosion should be considered for integrated CCS projects.

One of the industrial uses of supercritical or dense phase carbon dioxide is as a solvent. It can and does penetrate and saturate some non-metallic materials. This can cause problems for specific items such as seals, gaskets, instruments and valve bodies (Brown, 2010b).

6.4.13.1 Examples

Capture: The CO_2 stream is dehumidified as a part of the capture phase to prevent water condensation and corrosion in pipelines and allow use of conventional carbon-steel materials. CO_2 from most capture processes contains moisture, which needs to be removed to avoid corrosion and hydrate formation during transportation. Suitable corrosion resistant materials of construction need to be chosen where the water content is high enough for corrosion to take place. Nevertheless, the potential for CO_2 hydrate formation remains at lower temperatures.

Transport: Corrosion is one of the main reasons for incidents in CO_2 pipelines. For pipeline construction, it is important to choose the materials to be suitable for the type and level of impurities in the CO_2 stream.

Dry (<50 ppm moisture) CO_2 is not corrosive to the carbon-manganese steels commonly used for pipelines, even if the CO_2 contains other impurities such as oxygen, hydrogen sulfide and sulfur or nitrogen oxides.

A CO_2 stream containing a significant amount of moisture (e.g. 1 000 ppmv) is highly corrosive, so a CO_2 pipeline in this case should be made from a corrosion-resistant alloy. Some pipelines are made from corrosion-resistant alloys ("stainless steel 304L") (Goutier et al., 2010)[10], although the cost of materials is several times larger than carbon manganese steels.

9) Below a threshold (which is influenced by the other impurities dissolved within the CO_2) there are no "free water" molecules available to form carbonic acid, and the CO_2 stream is not corrosive of carbon steel. ISO 27913 discusses this in Annex A. A water content of <50 ppmv will probably not corrode carbon steel, and if it is a mixture of only CO_2/H_2O, the water content may be 500 ppmv before corrosion takes place (Ref. "Towards Hydrogen and Electricity Production with Carbon Dioxide Capture and Storage: CO_2 quality recommendations" Dynamis project, de Visser et al, 21 June 2007).

10) Oxidation of 304L stainless steel in a carbon dioxide atmosphere at 10 bar has been studied. Between 1 193 and 1 293 K the oxidation kinetics exhibit first a rapid increase, then a parabolic behaviour with apparent activation energy of (209 ± 8) kJ/mol and obeys a Langmuir pressure law. After 1,15 mg/cm^2, the kinetics become almost linear.

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Pipelines in operation are monitored internally by pigs (internal pipeline inspection devices) and externally by corrosion monitoring and leak detection systems.

Storage: Corrosion may cause a release of CO_2 from geological storage sites to the atmosphere and to the sea. A number of possible leakage pathways can occur along wells and abandoned wells, as illustrated in Figure 9. These include leakage between the cement and the outside of the casing (Figure 9 a), between the cement and the inside of the metal casing (Figure 9 b), within the cement plug itself (Figure 9 c), through deterioration (corrosion) of the metal casing (Figure 9 d), deterioration of the cement in the annulus (Figure 9 e) and leakage in the annular region between the formation and the cement (Figure 9 f).

The risk of leakage through wells is proportional to the number of wells intersected by the CO_2 plume, their depth, and the abandonment method used. The risks of corrosion leading to leakage may be higher in legacy wells, that have not been built and closed considering exposure to CO_2 and pressure increase, compared to injection or monitoring wells built for the purpose of CO_2 storage.

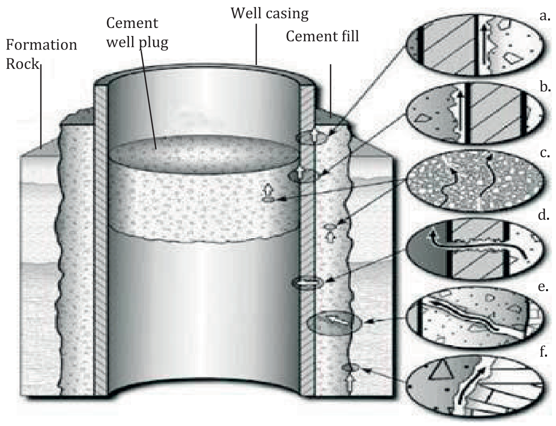

Figure 9 — Possible leakage pathways in an abandoned well (IPCC, 2005)

6.4.14 Pipeline crosscutting risks

Context

(XC, T→S→C)

Transportation of CO_2 through pipelines was first demonstrated with the Canyon Reef pipeline in 1972. Since then, a significant length of pipeline has been in operation both for “naturally occurring” and processed CO_2, as shown in Table 5 (IEA GHG, 2013; Bliss et al., 2009).

Table 5 — Operational CO_2 pipelines, worldwide

Name	Location	CO_2 source	Length km	Capacity Mt/y
Adair	USA	‘Natural’	24	1,0
Anton Irish	USA	‘Natural’	64	1,6
Beaver Creek	USA	‘Natural’	76	
Bairoil	USA	‘Natural’	258	23
Bati Raman	Turkey	CCS	80,5	
Borger	USA	‘Natural’	138	1,0
Boundary Dam	Canada	CCS	66	1,2
Bravo	USA	‘Natural’	351	7
Canyon Reef	USA	‘Natural’	224	4,3

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Table 5 *(continued)*

Name	Location	CO_2 source	Length km	Capacity Mt/y
Centerline	USA	'Natural'	182	4,3
Central Basin	USA	'Natural'	231,75	27
Chaparral	USA	'Natural'	37	1,3
Choctaw Lake (NEJD)	USA	'Natural'	294	7
Comanche Creek (currently inactive)	USA	'Natural'	193	1,3
Cordona Lake	USA	'Natural'	11	1,3
Cortez	USA	'Natural'	808	24
Decatur	USA	'Natural'	1.9	1,1
Delta	USA	'Natural'	174	11,4
Dollarhide	USA	'Natural'	37	1,6
El Mar	USA	'Natural'	56	1,3
Enid-Purdy	USA	'Natural'	188	1,6
Este I	USA	'Natural'	64	3,4
Este II	USA	'Natural'	72	2,6
Ford	USA	'Natural'	19	1,0
Free State	USA	'Natural'	138	7,0
Gorgon	Australia	'Natural'	8,4	4
Green Line I	USA	'Natural'	441	18.0
In Sarlah	Algeria	CCS	14	
Joffre Viking	USA	'Natural'	13	1,3
Lacq	France	CCS	27	0,06
Llaro	USA	'Natural'	85	1,6
Lost Soldier/Wertz	USA	'Natural'	47	
Mabee Lateral	USA	'Natural'	29	2,1
McEmo Creek	USA	'Natural'	64	1,6
Means	USA	'Natural'	56	2,6
Monell	USA	'Natural'	52,6	1,6
Netherlands	OCAP	'Natural'	97	0,4
North Cowden	USA	'Natural'	42	2,6
North Ward Estates	USA	'Natural'	13	1,6
PecosCounty	USA	'Natural'	42	1,6
Pikes Peak	USA	'Natural'	64	1,6
Powder River Basin CO_2 PL	USA	'Natural'	201	4,3
Qinshui	China	'Natural'	116	0,5
RavenBridge	USA	'Natural'	257	4,3
Reconcavo	Brazil	CCS	183	
RhourdeNouss-Quartzites	Algeria	'Natural'	30	0,5
Salt Creek	USA	'Natural'	201	4,3
Rosebud	USA	'Natural'		
SheepMountain	USA	'Natural'	656	11
Shute Creek	USA	'Natural'	48	23,6
Slaughter	USA	'Natural'	56	2,6
SnØhvit	Norway	CCS	153	0,7

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Table 5 *(continued)*

Name	Location	CO_2 source	Length km	Capacity Mt/y
Transpetco	USA	'Natural'	177	1,6
Val Verde	USA	'Natural'	134	2,1
West Texas	USA	'Natural'	97	1,6
Wellman	USA	'Natural'	42	1,6
Weyburn	Canada	CCS	330	2
White Frost	USA	'Natural'	18	1,3
Wyoming CO_2	USA	'Natural'	180	4,3
		Totals	>7 762	>243

It would be inaccurate to describe the transportation of CO_2 through pipelines as a novel technology, but it is recognized that the chemical composition of CO_2 captured from some industrial facilities and some capture technologies may differ from other capture sources.

While pipelines may be the method of choice for transportation of bulk CO_2 in CCS applications, there are others where is it not practicable or economic to provide this infrastructure. In these situations, or locations, transport of CO_2 by ship (or barge), rail or road may be economically more attractive, particularly when smaller amounts of CO_2 need to be moved over long distances or overseas. This subclause describes what experience is available, the risks associated with transporting CO_2 from CCS applications and the factors that should be taken into consideration.

Ship and Barge Transport

There is considerable experience in the transport of liquefied petroleum gases (LPG, principally propane and butane) on a large commercial scale by marine tankers. Pure CO_2 is transported by ship in much the same way [typically at 0,7 MPa – 1,8 MPa (Anthony Veeder Co) pressure and −40 °C], but this currently takes place on a small scale because of limited demand. Shipment of CO_2 already takes place on a small scale in Europe where ships transport food quality CO_2 (around 1 000 t) from large point sources to coastal distribution terminals.

The properties of liquefied CO_2 carried by ship are similar to those of LPG, and the technology could be scaled up to large CO_2 carriers if a demand for such systems were to materialise. Consequently, the larger-scale shipment of CO_2 with capacities in the range of 10,000 to 40,000 m^3, is likely to have much in common with the shipment of liquefied petroleum gas (LPG). There is already a great deal of expertise in transporting LPG, which has developed into a worldwide industry over a period of 70 years.

Hydrocarbon gas tanker ships are potentially dangerous, and the recognized hazard has led to high standards for design, construction and operation, and serious incidents are rare. Applying the same standards to CO_2 tankers would be expected to result in a similarly low accident rate. The design methodology for LPG cargo tanks is well understood and is regulated by international standards (specifically the "International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IMO, 1983)"; IGC code) and Classification Societies (such as DNV, BV and LRS).

Ship-platform collisions in the North Sea take place at about 2,8/year (Oltedal, 2012), worldwide the figures are about 1,5 and 4,3 for passing vessels and infield vessels respectively (2010). Liquefied Gas ship-ship interactions are estimated (IMO, 2007) as shown in Table 6.

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Table 6 — Estimated Liquefied gas Ship-Ship interactions (per ship per year)

Interaction	LPG carriers	LNG carriers
Collision	0,022	0,006 7
Contact	0,003	0,002 8

Road and Rail Transport

Road and rail tankers also are technically feasible transport options and have been commonplace for over 40 years. These systems transport CO_2 at a typical temperature of −20 °C and at about 2 MPa pressure in insulated steel vessels as liquid. Trucks are used at some project sites, moving the CO_2 from where it is captured to a nearby storage location. Given the large quantities of CO_2 that could be captured via CCS in the long term, it is unlikely that truck and rail transport will be significant. Generally, this has been a safe method of transporting carbon dioxide. There have been a small number of incidents reported during loading/unloading over the years with at least one of these being fatal (Berkeley Power Station Gloucestershire, circa. 1983).

Examples of Crosscutting risks[11)]

Crosscutting risks for CO_2 transportation can be split into three types, Commercial, Stakeholder Management, and Design and Construction.

- Commercial
  - Unexpected behaviour of CO_2 streams in other projects prompts redesign and delays implementation (an example of this might be that ductile fracture propagation observed in tests for a particular CO_2 mixture is observed in a way not predicted theoretically by the Battelle Two Curve Method).
  - Costs and delays to implement additional health, safety and environment requirements (an example of this might be validation of dispersion models, such as PHAST, with impure CO_2, which has different thermodynamic properties from pure CO_2).
  - Price fluctuations related to novel or CCS-specific components (an example of this could be tilting of pipeline steel costs following decisions to construct significant amounts of transmission infrastructure).
  - Availability, price and terms of project insurance for CCS-specific elements (particularly in the unlikely event that there is an unplanned release of CO_2 from a CCS application which results in significant exposure to the insurance company).
- Stakeholder Management
  - CCS protest groups disrupting work (an example of this might be local action groups generating public opposition which causes construction permits to be withdrawn for part of the CCS chain).
- Design and Construction
  - Non-availability of suitable CCS design standards (a paucity of clear design standards can lead to a ratchetting-up of, for instance, reserve factors, resulting in unnecessary costs and projects becoming financially unviable).
  - Unexpected behaviour of CO_2 streams in other projects prompts a redesign (an example of this might be the discovery that design moisture levels were too high to avoid corrosion in the pipeline, necessitating the design and construction of an additional dehumidification plant upstream).

11) Defined as “risks associated with integrating various elements of the CCS project”.

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    — Design raises significant CCS technical issues (an example of this might be incompatibility of the CO_2 stream with some of the key pipeline components, necessitating the design, financing and construction of an additional processing plant at the capture end).

    — Technology maturity and availability of CCS specific components and hardware (recognizing that there are few demonstration plants working at the moment).

— Intermodal Transport

  In a CCS system context, intermodal describes transportation using different modes of conveyance in conjunction with each other, such as ships, pipelines and road vehicles. Intermodal transportation of impure CO_2 carries with it not just the risks associated with the individual transportation methods, but also those associated with intermediate storage and transfer between one mode of transport and another (e.g. rail-to-ship). These risks are expected to include:

    — integrity of flexible pipes between storage vessels that are designed to move and those that are not (e.g. CO_2 capture plant-to-railcar, road trailer-to-diurnal storage vessel, ship-to-shore or platform);

      NOTE Risks are reduced at lower pressure (<10 bar), where there is significant experience with pure CO_2 from industrial gasses industries.

    — increased potential for human error while making and breaking temporary connections between one mode of conveyance and another;

    — potential for phase changes in the CO_2 resulting from pressure differentials between, for example, a full railcar and an empty storage vessel;

    — risks to intermediate storage facilities from external influences (e.g. CO_2 collected from diverse sources by road or rail may be stored at pressure in the dockside pending the arrival of a ship) such as terrorist action, aircraft crashes, earthquakes or flooding;

    — Boiling Liquid Expanding Vapour Explosion (BLEVE) during transfer from a high pressure vessel to a low pressure vessel. A CO_2 BLEVE, which resulted in three fatalities, took place at Worms, Germany, on 21st November 1988;

    — increased potential for CO_2 quality (composition) to be compromised.

7 Considerations for a potential ISO standard addressing lifecycle risks for integrated CCS projects

This document reviews existing best practices, regulations, and standards for assessing and managing the lifecycle risks associated with integrated CCS projects. It focuses specifically on two types of risk: overarching and crosscutting risks. Overarching (OA), or overall risks are risks that affect the entire CCS project. Crosscutting (XC) risks are risks that affect more than one part of a CCS project chain. Integration risks are considered crosscutting for the purposes of this document. This document includes an inventory of these risks, and describes examples where these risks have affected CCS projects. The risks identified in the inventory (see Clause 5) may not be present in every CCS project situation.

This document contains information that will be valuable for writing a standard which provides guidance for processes to be addressed by a CCS project operator. Such a standard would articulate and describe procedures designed to ensure that important overarching and crosscutting risks have been comprehensively sought, evaluated, and addressed. The OA and XC risks listed in Clause 5 should not become a default list that is deemed to be comprehensive, but can serve as a starting set of examples.

As described in Clause 4, lifecycle risk assessment and management is practiced in CCS Projects and has been addressed by various regulations, best practices, and standards. Within this area of practice, the OA/XC/Lifecycle topics described in this document are addressed through a process requiring a project-specific risk assessment.

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A potential standard for lifecycle risks for integrated CCS projects might specify issues such as:

a) An integrated project establishing and following a process to seek and evaluate OA/XC risks, starting with the ones in this document (q.v.);

b) An integrated project establishing and following a process to treat (reduce and manage) the evaluated OA/XC risks, including assignment of responsibility and accountability; and

c) An integrated project documenting and publishing (making available) information about the risk management processes that were followed, so that later projects can improve upon the practice.

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Annex A
(informative)

List of acronyms

ALARP	As Low As Reasonably Possible
AHP	Analytic Hierarchy Process
BHP	Bottom Hole Pressure
BLEVE	Boiling Liquid Expanding Vapour Explosion
BP	British Petroleum
BRGM	Bureau de recherches geologiques et minieres, The French Geological Survey
BV	Bureau Veritas
CASSIF	Carbon Storage Scenario Identification Framework
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilization, and Storage
CDM	Clean Development Mechanism
CFR	Code of Federal Regulations
CO_2	Carbon Dioxide
CSA	Canadian Standards Association
DGC	Dakota Gasification Company
DIS	Draft ISO Standard
DNV	Det Norske Veritas
DNV GL	Det Norske Veritas Germanischer Lloyd
EIA	Environmental Impact Analysis (or Assessment)
EOR	Enhanced Oil Recovery
ENSO	El Niño-Southern Oscillation
EPA	Environmental Protection Agency
ETA	Event Tree Analysis
ETS	Emissions Trading Scheme
EU	European Union
FEP	Features, Events, Processes

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FRAM	Framework for Risk Assessment and Management
FTA	Fault Tree Analysis
GCCSI	Global CCS Institute
GS	Geological sequestration
H_2O	Water
HAZOP	Hazard and Operability
HRA	Health Risk Assessment
HSE	Health, Safety and Environment
IEA	International Energy Agency
IEAGHG	International Energy Agency Greenhouse Gas Programme
IEC	International Electrotechnical Commission
IES	International Electrotechnical Commission
IGC	International Gas Code
IGCC	Integrated Gasification Combined Cycle
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
IRS	Internal Revenue Service
IRSM-CAS	Institute of Rock and Soil Mechanics, Chinese Academy of Sciences
ISGS	Illinois State Geological Survey
ISO	International Standards Organization
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
LRS	Lloyd’s Register of Ships
MANAUS	Methodology of Analysis Unified and management of risks of geological Storage of CO_2
MEP	Ministry of Environmental Protection (China)
METI	Ministry of Economy, Trade and Industry
MMV	Measurement, Monitoring and Verification
MOE	Ministry of Environment
MPa	Mega Pascal
MS	MicroSoft
MVA	Monitoring, Verification, and Accounting

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NETL	National Energy Technology Laboratory
NOx	Nitrous Oxides
O_2	Oxygen
OA	Overarching
OSPAR	Parties to the Convention for the Protection of the Marine Environment of the North-East Atlantic
PA	Performance Assessment
PHA	Preliminary Hazard Analysis
PTRC	Petroleum Technology Research Centre
RCSP	Regional Carbon Sequestration Partnerships
RISQUE	Risk Identification and Strategy Quantitative Evaluation
SINOPEC	China Petroleum and Chemical Corporation
SOx	Sulfur dioxides
SRB	Sulfate-Reducing Bacteria
SRF	Screening and Ranking Framework
TNO	Netherlands Organization for Applied Scientific Research
UNFCCC	United Nations Framework Convention on Climate Change
UK	United Kingdom (of Great Britain and Northern Ireland)
USA	United States of America
USDOE	United States (of America) Department of Energy
USDW	Underground Source of Drinking Water
VEF	Vulnerability Evaluation Framework
WAG	Water Alternating Gas
WRI	World Resources Institute
XC	Crosscutting

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