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Lifecycle risk management for integrated CCS projects

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National foreword

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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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Contents

Page

Foreword ... **v**

Introduction ... **vi**

1 Scope ... **1**

2 Normative references ... **2**

3 Terms and definitions ... **2**

4 General information on lifecycle risk management for CCS ... **2**
- 4.1 Usefulness and benefits of lifecycle risk management ... 2
- 4.2 Defining lifecycle for an integrated CCS project ... 2
- 4.3 Examples of overarching risk assessment processes conducted for CCS projects ... 5
- 4.4 Examples of ISO risk standards that may be applied to CCS projects ... 8
- 4.5 Description of how risk is addressed in other standards and regulations ... 9
  - 4.5.1 General ... 9
  - 4.5.2 Treatment of CCS risk in international agreements ... 9
  - 4.5.3 CSA Standard (Z741-12, Geological Storage of Carbon Dioxide) ... 12
  - 4.5.4 US DOE Best Practices for Risk Analysis and Simulation for Geologic Storage of CO_2 ... 13
  - 4.5.5 WRI CCS Guidelines ... 13
  - 4.5.6 IEA Carbon Capture and Storage Model Regulatory Framework ... 14
  - 4.5.7 United States EPA regulations ... 14
  - 4.5.8 EU Directive 2009/31/EC on the geological storage of carbon dioxide ... 15
  - 4.5.9 Regulation of geological storage in Japan ... 16
  - 4.5.10 Technical guidelines for CCS in China ... 16
  - 4.5.11 Summary of key features of CCS risk assessment requirements ... 17

5 Overarching and crosscutting aspects of risk management in CCS projects ... **18**
- 5.1 Introduction ... 18
  - 5.1.1 Scope ... 18
  - 5.1.2 Terms relating to risk ... 18
  - 5.1.3 Project components and phases ... 19
  - 5.1.4 Responsibilities and risk ownership ... 19
- 5.2 Risk identification ... 19
  - 5.2.1 General ... 19
  - 5.2.2 Identifying overarching and crosscutting (OA-XC) risks ... 20
- 5.3 Rating and evaluating risk ... 24
  - 5.3.1 Risk assessment, risk tolerance, and risk evaluation processes ... 24
  - 5.3.2 Risk scales and expert judgment ... 24
  - 5.3.3 Risk evaluation for overarching or crosscutting risks ... 25
- 5.4 Risk treatments ... 25
  - 5.4.1 General ... 25
  - 5.4.2 Aspects of risk treatment that are overarching and/or crosscutting ... 25

6 Inventory of overarching and crosscutting risks ... **25**
- 6.1 General ... 25
- 6.2 Identification of overarching and crosscutting risks over the lifecycle of CCS projects ... 26
- 6.3 Overarching risks ... 26
  - 6.3.1 Over-arching risks ... 26
  - 6.3.2 Policy uncertainties ... 27
  - 6.3.3 Uncertain cost or regulations for integrated project ... 28
  - 6.3.4 Engagement ... 29
  - 6.3.5 Project permits not obtained ... 29
  - 6.3.6 Lack of or changes in financial driver ... 30
  - 6.3.7 Changes in financial factors external to the project/Insufficient project financial resources/Changes to the cost of capital ... 31
  - 6.3.8 Unexpected construction or operational cost changes ... 32

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Full document details: PD ISO/TR 27918:2018

6.3.9 Uncertainty in CO_2 supply ... 32
6.3.10 Lack of emissions accounting ... 34
6.3.11 Technology scale-up ... 34
6.3.12 Lack of knowledge or qualified resources for operating the unit ... 35
6.3.13 Project impacts on the environment ... 35
6.3.14 External natural impacts on project ... 36
6.3.15 External man-made impacts on project ... 36
6.3.16 Conflicts with other land-use rights ... 37
6.4 Crosscutting risks ... 39
6.4.1 General ... 39
6.4.2 Accidental or intentional interruption or intermittency of CO_2 supply, CO_2 intake or transportation ... 40
6.4.3 Shared infrastructure by multiple projects (uncertain ownership, performance or lack of coordination) ... 41
6.4.4 Using existing facilities ... 42
6.4.5 Unintended phase change variations in quality and quantity of the CO_2 stream ... 43
6.4.6 CO_2 out of specifications/Source gas composition not as expected ... 44
6.4.7 Mismatched component performance ... 48
6.4.8 Lower capture efficiency due to the upstream plant flexible operation ... 50
6.4.9 Insufficient storage resource ... 51
6.4.10 Reservoir not performing as predicted ... 52
6.4.11 Model uncertainties regarding the storage performance ... 53
6.4.12 Lack of maintenance and emergency control procedures/safety-related accidents ... 55
6.4.13 Corrosion and material problems ... 58
6.4.14 Pipeline crosscutting risks ... 59

7 Considerations for a potential ISO standard addressing lifecycle risks for integrated CCS projects ... 63

Annex A (informative) **List of acronyms ... 65**

Bibliography ... 68

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Documents
Document Sharing Hub
Full document details: PD ISO/TR 27918:2018

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

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).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

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.

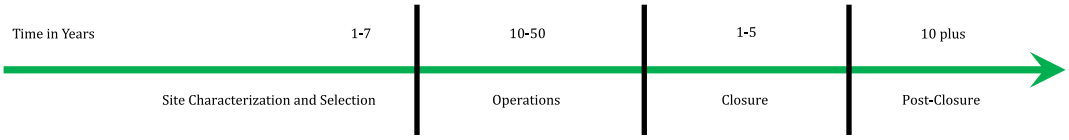

Figure 1 — Timeline for a CCS project defined in the WRI guidelines for carbon dioxide capture, transport, and storage (Forbes et al., 2008)

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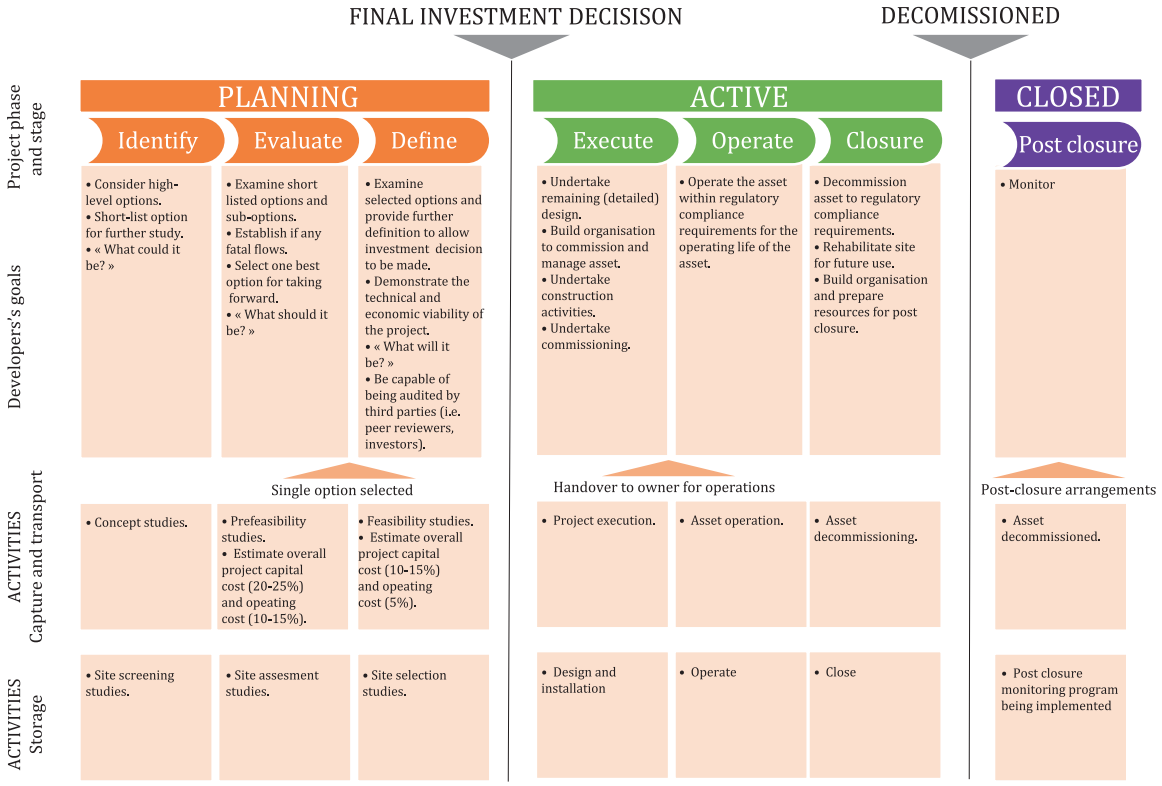

Figure 2 — The project Lifecycle Model of a CCS project developed by the Global CCS Institute (GCCSI, 2015)

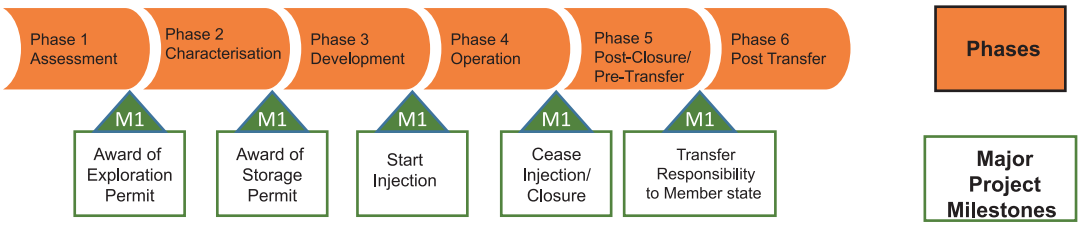

Figure 3 — CO_2 storage lifecycle phases and milestones described in the guidance document of the implementation of Directive 2009/31/EC (European Communities, 2011)[2)]

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

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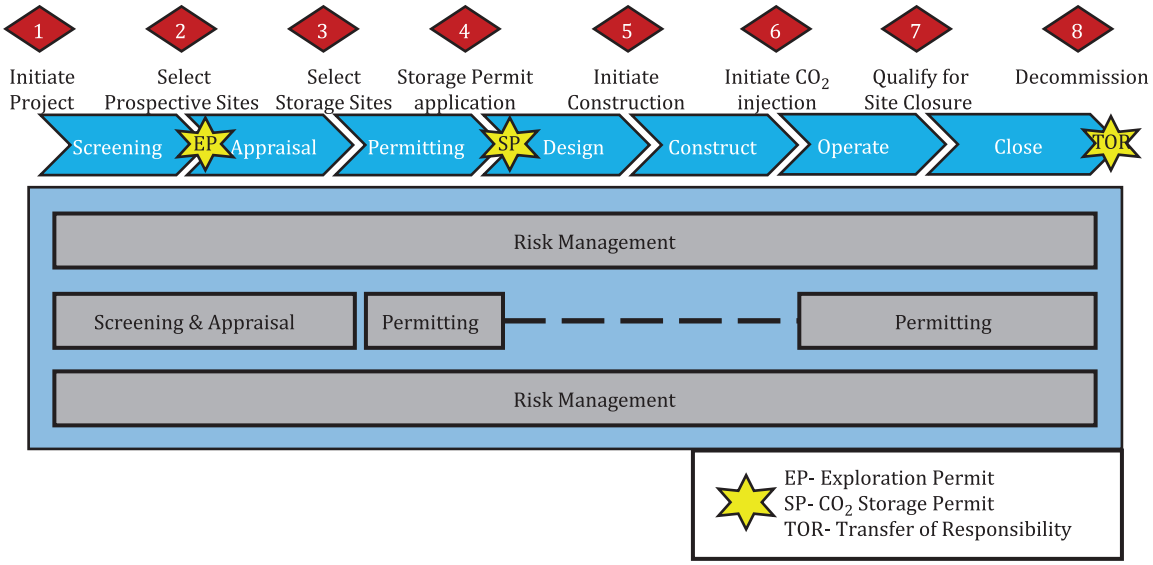

Figure 4 — Carbon dioxide geological storage project lifecycle and associated qualification statements, relevant permits and project milestones defined by DNV (DET NORSKE VERITAS AS, 2012; Det Norske Veritas, 2009)

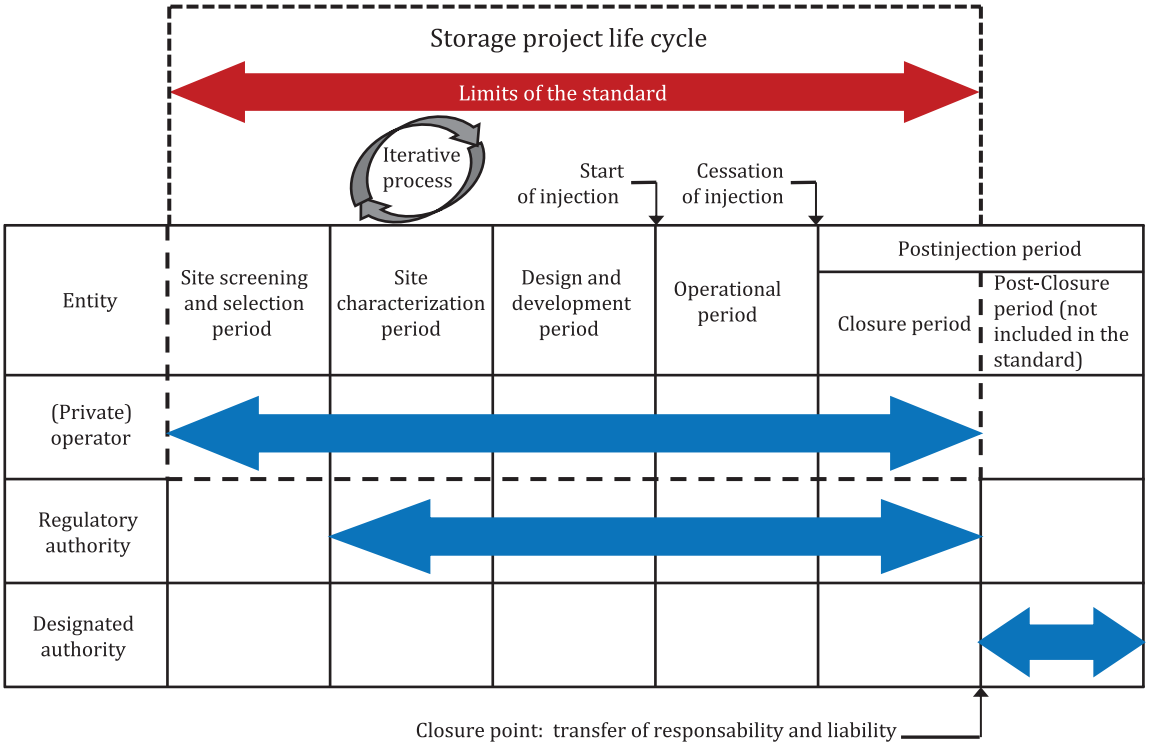

Figure 5 — Lifecycle of a CCS project as defined in Z741 (Canadian Standards Association, 2012)

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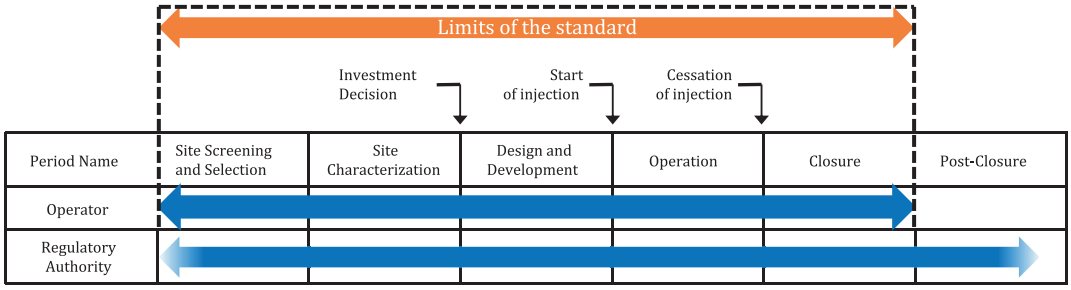

Figure 6 — Lifecycle of a CCS project as defined in in the International Standard for Carbon Dioxide Capture, Transportation, and Storage—Geologic Storage (ISO DIS/27914)

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.

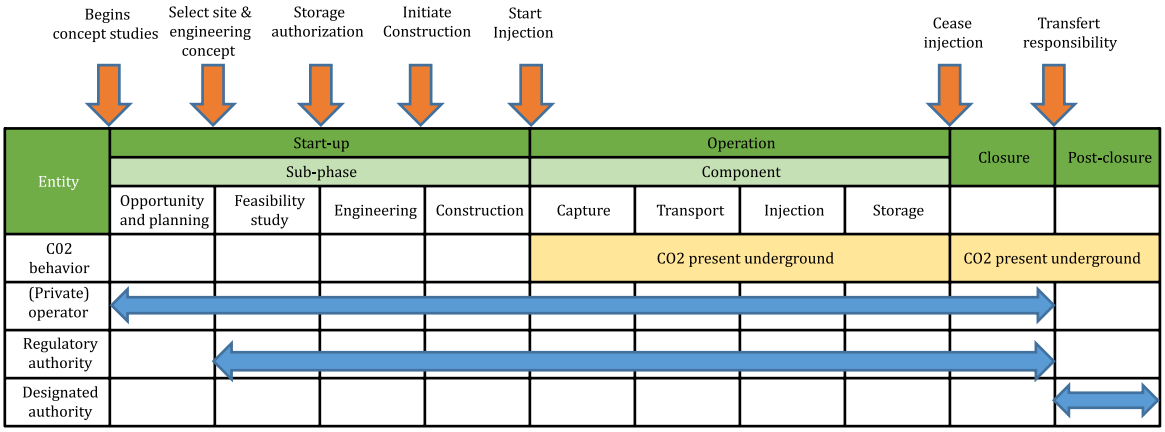

Figure 7 — Proposed CCS project lifecycle from a risk management viewpoint

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			Closure	Post-closure
		Opportunity	Planning	Engineering	Construction	Capture	Transportation	Injection		
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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