Chapter 4
Environmental Impact Assessment and CCS Guidance

Abstract Avoiding the adverse impacts of carbon capture and storage activities on the environment and human health would require careful site selection, effective regulatory oversight, and appropriate monitoring program. The strategic environmental assessment and environmental impact assessment are procedural tools for evaluating and assessing possible environmental effects of a policy or certain project. This chapter provides the overview of the principles and methodology for strategic environmental assessment and environmental impact assessment for carbon capture and storage activity. The guidelines of carbon capture and storage activities to accomplish strategic environmental assessment or environmental impact assessment are also discussed and illustrated.

4.1 Strategic Environmental Assessment (SEA)

Strategic environmental assessment (SEA) methodology is a widely recognized and useful tool when structuring environmental aspects and performing the environmental impact assessment of large projects. It was laid out in Directive 2001/42/EC on the assessment of the effects of certain plans and programs on the environment [1], which has been transposed into legislation, i.e., Statutory Instrument 2004 No. 1633 [2]. An SEA is a systematic process for evaluating environmental consequences of proposed policies, plans, and programs to ensure the consequences are fully understood and appropriately addressed from the earliest stages of decision making [3–5]. As a result, the SEA should be transparent and suitable for communication with stakeholders that show a greater interest in the concept. Most practitioners consider SEA as a decision-aiding process rather than a decision-making process [5].

Governmental programs which contain decisions on the appointment of possible locations or routes or the consideration of alternative locations or routes for CCS activities are expected to be SEA-obligated [6]. In general, the SEA is undertaken at an earlier stage in the decision-making process than an environmental impactassessment (EIA) to ensure that environmental considerations are properly integrated into this stage of the decision-making process. In most cases around the

P.-C. Chiang and S.-Y. Pan, *Carbon Dioxide Mineralization and Utilization*, DOI 10.1007/978-981-10-3268-4_4

world such as the Netherlands [7], the permit for deploying a CCS project requires an EIA procedure. The purpose of the EIA is to clarify the potential effects of a CCS project on the environment, economy, natural resources, and society. More details regarding the EIA procedure are illustrated in Sect. 4.2.

4.1.1 Methodology and Framework

The objectives of SEA are to broadly present the preferred environmental, ecological, social, and economic outcomes to minimize detrimental effects of a project or activity. The SEA Directive does not have a list of plans or programs similar to the EIA [4]. Since the plans and programs proposed by the private sector may have considerable environmental impacts, the voluntary use of SEA methodology is encouraged. So far, the SEA has mainly been used for the evaluation of public infrastructure policies, programs, and plans [5, 6]. The methodology of the SEA basically comprises of five phases:

- Phase 1: Screening
  - Determination of obligation
  - Identification of key factors
  - Judgment by competent authority
- Phase 2: Scoping
  - Public notification
  - Public consultation
  - Determination of system boundary
- Phase 3: Formulation, analysis, and valuation
  - Formulation of environmental report
  - Analysis of current state (business-as-usual) of the environment
  - Description of alternatives to the plan
  - Publication of preliminary plan and environmental report
- Phase 4: Assessment
  - Public consultation
  - Decision making and action plans
  - Determination of key performance indicators
- Phase 5: Evaluation
  - Performance check
  - Evaluation of environmental impacts

Within the framework, the available baseline information could be collected. Although general guidelines exist, SEA guidelines and the best practice framework do not exist for applying to a CCS program. In the case of developing a CCS program, all activities that will be carried out to construct, operate, and close a CCS facility and all factors that could be affected by the above activities should be considered in the SEA [3]. Accordingly, the scope and boundary of the SEA would be determined. In the scoping stage, several strategies could be considered for future developments [5]:

- To widen the scope of assessment
- To expand the consultation requirements
- To increase the consideration of sustainability issues and health impacts

Afterward, the environmental impacts of different alternatives would be analyzed and quantified. In the following valuation step, preferable technical alternatives would be identified and weighted. From the results of the valuation, the best and worst alternatives with respect to the CCS program can be identified for the decision-making procedure.

4.1.2 Screening Key Aspects and Available Information

Since SEA is a key tool in sustainable development strategic decision making, it is usually applied at an earlier stage in a CCS development than EIA. The screening stage is the first step of the SEA to define the key aspects and issues for proposing an SEA work plan. Typically, a screening matrix with an overview of the status of knowledge in different environmental areas would be developed. It is suggested that SEA should be used when strategic-level decisions are being made for alternatives options and preferred options [5].

An essential part of the SEA process is to identify the current baseline of environmental conditions as a "business-as-usual" scenario. Most of the environmental issues relating to CCS are with the engineering aspect, e.g., ensuring the CO_2 remains in the storage reservoir for hundreds to thousands of years without significant leakage or seepage [5]. These two issues of engineering and environment are inevitably entwined. In other words, it is only with sufficient knowledge of the existing conditions that the key issues may be properly identified and addressed through the assessment. Therefore, it should be addressed from a strategic environmental perspective through the creation of minimum national or international standards and requirements for site selection, including [5] the following:

- Geology
  - Seal thickness and integrity
  - Fluid compatibility
  - Geochemical reaction
- Reservoir Property Assessment
- Well

  - Disposal well selection
  - Design (cementing, materials, corrosion) and modelling
  - Monitoring

- Others

  - Surrounding environment conditions
  - Failure of wells and pipelines
  - Lateral migration potential

To determine suitable areas that might be acceptable for CCS, the above components should be carefully considered in the SEA. In addition, the minimum standards need to be used in tandem with good operational and monitoring procedures [5]. Since each individual CCS project has different characteristics, the generic standards would have limitations in the level of achievable protection.

4.1.3 Technical Description of Alternatives for CCS

CCS involves three stages: (1) capture and concentration, (2) transport, and (3) storage. Although the three distinctive steps of CCS are formally separated activities, an integrated approach to combining the separate EIA procedures for CCS activities into one procedure, or at least to provide close linkage between them, should be considered. For CCS, the capture of CO_2 from industries and/or power plants using fossil fuel combustion can be done by separating CO_2 from the flue gas either prior to fuel combustion or post-combustion. There are a range of CCS technologies at different stages of development. Therefore, in the SEA, characteristics and processes of CO_2 generation sources and various technical alternatives for CCS should be comprehensively described.

The components of the CCS system are briefly illustrated in the following content. More general information regarding carbon capture, utilization, and storage technologies can be referred to in Chaps. 2 and 3 in this book.

4.1.3.1 CO_2 Capture

Currently, several technologies for capturing, transporting, and storing CO_2 from coal-fired power plants are available in the literature. For CO_2 capture, four main technical alternatives could be considered:

- Precombustion capture
- Post-combustion capture
- Oxy-fuel combustion capture
- Industrial separation from natural gas processing, ammonia production, etc.

4.1.3.2 CO_2 Transport

Normally, CO_2 is captured as a gas and needs to be compressed (or cooled) for the transport process. For CO_2 transport, various alternatives could be considered:

- Pipeline (i.e., onshore and offshore)
- Shipping (i.e., offshore)
- Truck
- Railway

From the economical feasibility point of view, large-scale transport options are shipping and pipeline, while truck and train are possible means of transport for small-scale projects in the start-up phase of a CCS program. Typically, pipeline is the best alternative for transporting large quantities of CO_2 onshore, e.g., >1 Mt/year [3], which is a commercial technology. Tankers would generally only be functional for smaller volumes, e.g., $\sim$1 Mt/year [5].

4.1.3.3 CO_2 Storage

For CO_2 storage, the following alternatives could be considered:

- Enhanced oil recovery (EOR) or enhanced gas recovery (EGR)
- Enhanced coal bed methane recovery (ECBM)
- Saline reservoirs
- Depleted hydrocarbon reservoirs
- Ocean storage (e.g., dissolution type or lake type)
- Mineral carbonation

The captured CO_2 can be stored both in onshore terrestrial geological formations and in offshore subseabed geological formations. In addition, although other options (such as ocean storage) exist, they are either in early phases of development or demonstration phases.

4.2 Environmental Impact Assessment (EIA)

Table 4.1 presents the comparison of EIA and SEA for CCS activities. Similar to SEA, the concept of EIA refers to the examination, analysis, and assessment of the proposed activities with a view to ensure environmental, social, and economic integrity for achieving long-term sustainable development. In particular for certain CCS activities, the comprehensive environmental and socioeconomic impact assessments should be thoroughly performed from a life cycle approach. In other words, with specific relation to CCS, an EIA would be conducted to a particular CCS project, while an SEA would examine CCS opportunities and policy on a regional basis (e.g., country wide).

Table 4.1 Comparison of environmental impact assessment (EIA) and strategic environmental assessment (SEA) for CCS activities

Category	EIA	SEA
Feature	Usually reactive to a proposed CCS development proposal	Proactive and informs CCS development proposals
Assessment contents	The effect of a proposed CCS development on the environment	• The effect of CCS policy, plans, or programs on the wider environment • The effect of the environment on the CCS development needs and opportunities
Target	A specific proposed CCS project	Areas, regions, or sectors of CCS development
System boundary	A well-defined beginning and end	A continuing process aimed at providing information at the right time
Impacts assessment	Direct impacts and benefits of a proposed CCS project	Cumulative CCS impacts and identifies implications and issues for a sustainable development
Focus	• Mitigation of CCS impacts and possible CO_2 leakages • Specific impacts of a proposed CCS project	Maintaining a chosen level of environmental quality
Perspective	A narrow site-specific perspective and a high level of detail	• A wide global perspective and a low level of detail to provide a vision and overall framework. • Provides a review of cumulative global effects of CCS

Courtesy of [5]

With the EIA procedure, the relevant information on environmental impacts required for various administrative decisions is gathered in a single report: the environmental impact statement (EIS). The EIS report should represent the knowledge base on environmental impacts due to the activity and is used as reference work in the decision making process [6].

Currently, CCS projects are not specifically mentioned in EIA around the world since the CCS relevant technologies are relatively new and under development [5]. However, in some cases (such as in the EU), CCS projects may be constrained by existing legislation. To ensure capture of a CCS development may be to amend EIA legislation in national countries by suggesting that the CCS projects are specifically required to be subject to an EIA [5]. Although legislation usually refers to guidelines for conducting EIAs, in many cases, it does not specifically require the use of the guidelines.

4.2.1 Methodology and Framework

A variety of frameworks for EIA procedures can be found in international guidelines, the European Union, and core countries, but they are fundamentally similar.

In many cases, some elements of the good practice of EIA are not actually required by law [5]. Det Norske Veritas (DNV) Ltd has proposed the best practice of the EIA procedure, which is based on International Finance Corporation guidelines combined with best practices identified from countries where DNV operate. With regard to compliance with CCS best practices, EIA frameworks may require amendments to ensure that the minimum requirements for acceptance by mechanism, such as clean development mechanism (CDM) and joint implementation (JI), can be achieved. The roles of CCS in the CDM are discussed in Sect. 4.3.4.

Generally, the EIA is used to safeguard environmental interests in the face of normally highly positive economic and socially beneficial impacts. The suggested stages for conducting EIAs are as following:

- (Stage 1) screening and scoping
- (Stage 2) analysis of alternatives
- (Stage 3) project descriptions
- (Stage 4) review on environmental baseline and legislation
- (Stage 5) impact assessment
- (Stage 6) environmental management plan for impact mitigation
- (Stage 7) environmental monitoring plan
- (Stage 8) reporting and review
- (Stage 9) project implementation and operations

Any possible risks or uncertainties that could cause the CCS project to be abandoned should be identified in the EIA. The risks and uncertainties can be determined via various approaches.

This can provide an overall insight into the environmental burdens of the entire CCS chain, thereby being able to streamline various decision-making procedures. Since the designs of CCS chain networks consist of multiscale concerns, a sound decision-making framework at material, process, and supply chain levels is required. Various approaches could be applied to achieve the goal, such as a hierarchical and multiscale framework to minimize investment, operating costs, and material costs, as shown in Fig. 4.1 [8]. In all cases, the best available techniques should be applied to ensure high-level protection for the environment and for communities [9].

Currently, a wide variety of methods have been used in the EIA, such as

- Life cycle assessment (LCA) [6]: quantification of the environmental impacts
- Environmental risk assessment (ERA) [10]: identification of potential hazards of a proposal to manage uncertainty
- Acoustics models [11]: calculation of the sound propagation in ocean
- Geodetic deformation analysis [12]: determination of the trend of movements (displacements) for all the common points in a monitoring network
- Water discharge analysis [13]: identification of thermal and waste substances during water discharge
- Other forms of surveys: ecological, archeological, geo-hydrological analyses

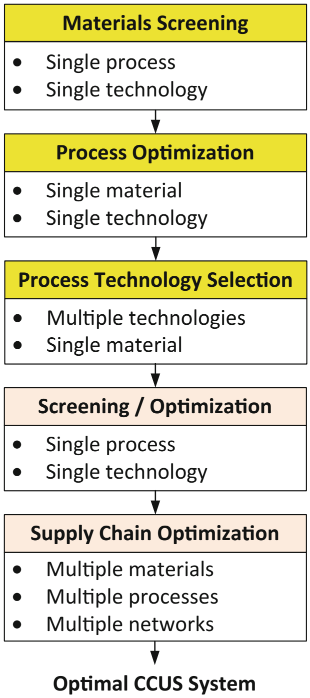

Fig. 4.1 Framework of multiscale systems engineering for CO_2 capture, utilization, and sequestration (CCUS)

In an EIA, different decision-making procedures for obtaining permits or exemptions are incorporated into a single procedure [7]. The EIA can be influenced by third parties by requesting additional and/or challenging information. Therefore, the possibility of public participation could play a key role in the public perception and rules of acceptation of CCS. It suggests that the following requirements and guidelines for a CCS project should be incorporated in the environmental assessment to avoid a significant release of CO_2 [5]:

- An integrated environmental, social, and health impact assessment (EHSIA) approach
  - Identification of environment resources
  - Requirement of operator commitment for monitoring
  - Provision of handing long-term liability
  - Consideration of storage performance assessment (SPA) as an inherit part
- A risk-based source-pathway-receptor approach
  - Identification of project with high risks of early closure
  - Evaluation of a carbon balance across the entire project life cycle
  - Provision of clear regulatory guidance on the play-off in priorities between local pollution concerns and climate change concerns

4.2.2 Environmental and Natural Resource Aspect

To include the environment in the decision-making process on permits and investments of the involved parties, EIA is usually introduced to quantify the environmental impacts of specific activities. The purpose of the EIA is to evaluate different alternatives and find the best option, in terms of environmental benefits, for a certain project.

For the purpose of permanent storage of CO_2, the environmental impact of a CCS project highly depends on (1) the characteristics of underground geological formation, (2) overpressure issues of the reservoir, and (3) lithologies adjacent to the storage reservoir [14]. The potential environmental impacts that may arise from CCS activities include the following:

- Air emissions: particulate matter, nitrogen oxides, sulfur oxides, dust, mercury, polycyclic aromatic hydrocarbons, etc.
- Water use associated with current CCS technologies: enhanced oil recovery (EOR)
- (Ground) water pollution: lubricant for drilling operations
- Solid waste generation: during drilling operations
- Noise: disturbing levels of noise
- Human health and safety: health of population
- Biodiversity: impact on ecosystems and habitats
- Geology: landscape, soils, and underground space.

On the other hand, the potential natural resource impact that may be caused from the CCS activities includes the following:

- Resources and raw materials: natural asset, energy source
- Waste utilization: management hierarchy

4.2.3 Socioeconomic Aspect

From an economic point of view, the cost of geological storage of CO_2 is highly site-specific, depending on factors such as (1) the location of the project (onshore or offshore), (2) the number of wells for injection, and (3) the depth of the storage formation. However, in all cases, the costs for storage (including monitoring) typically are in the range 0.6–8.3 US\$/t-CO_2 stored [15]. The potential socioeconomic impacts that may result from the CCS activities include the following:

- Traffic and transport: travel and transport on communities
- Economy and skills
- Archeology and cultural heritage: heritage resources, historic building, archeological features.

4.3 CO_2 Capture and Storage (CCS) Guideline

Geological storage of CO_2 has drawn extensive attention around the world from a concept of limited interest to one that is quite widely regarded as a potentially important mitigation option, as shown in Fig. 4.2. It is noted that the density of CO_2 will increase with depth. Until at about 800 m deep or greater, the injected CO_2 will be in a dense supercritical state [15].

4.3.1 Challenges

The existing challenges for widely deploying CCS activities as a CO_2 emissions control option [16] could be categorized into four aspects:

- Institutional barriers:
  - Building public understanding, awareness, and acceptance.
- Regulatory barriers:
  - Establishing an adequate legal and regulatory framework to support broad CCS deployment, including dealing with long-term liability;

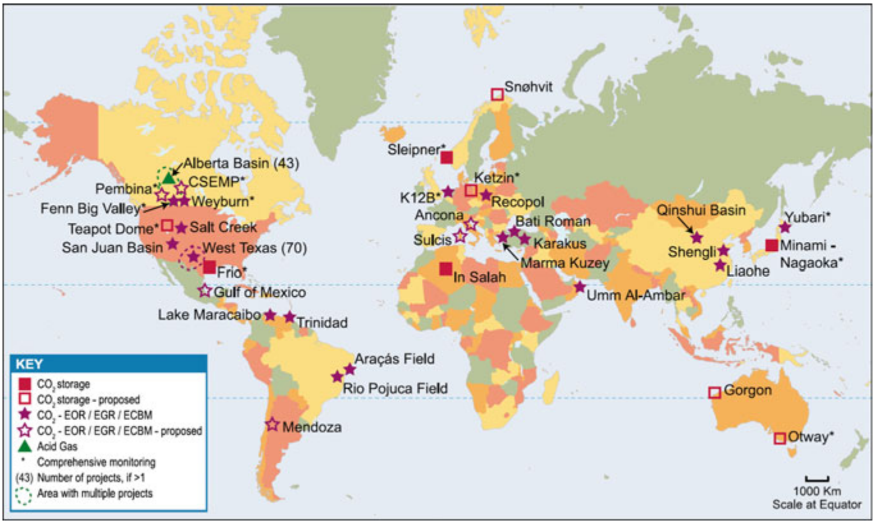

Fig. 4.2 Location of geological storage sites where CCS activities are planned or under way (courtesy of Special Report of the Intergovernmental Panel on Climate Change IPCC, Carbon Dioxide Capture and Storage, © Intergovernmental Panel on Climate Change 2005, published by Cambridge University Press ISBN 9780521866439 [15])

- Technological barriers:
  - Addressing the cost and energy penalty of capture;
  - Proving CO_2 storage permanence;
  - Verifying that sufficient storage capacity exists;
  - Developing best practices for the life cycle of a CCS project, from site selection through to site closure and post-closure monitoring.
- Financial barriers:
  - Global need for significant financial investments to bring numerous commercial-scale demonstration projects online in the near future;

4.3.2 Risk of CO_2 Release

The CO_2 storage site is the key area of risk in the CCS chain. It is noted that the risk of CO_2 release into the atmosphere during the phases of injection and storage exists. In general, the injection phase has a relatively limited period of operation, e.g., $\sim$50 years. Based on experience with the oil and gas industries, the risk of release of significant CO_2 is estimated to be 10^{-3} per reservoir per annum [5]. One of the major reasons is due to the corrosion of injection equipment, which could be controlled to less than 2.5 μm/pa by using polyethylene. However, more experience from CCS trials should be collected to confirm the available information from oil and gas injection wells. Other possible CO_2 release pathways include the following:

- Failure of abandoned wells and/or wellbore
- Diffusion flow through caprock via faults or by buoyancy through permeable zones
- Dissolution and transport of CO_2 charges waters by groundwater flow (most important leakage mechanism from aquifers)

Scientific knowledge and industrial experience can serve as a basis for appropriate risk management. Mapping of the reservoir and surrounding area should be a critical component to reduce the risk of CO_2 release from the storage site. In addition, risk management would need to incorporate the results of the storage performance assessment (SPA), which could be as an inherent part of EIA, as shown in Fig. 4.3. Furthermore, both a better understanding of the impact of impurities and the development of a suitable modelling technique are essential to predict the short- and long-term fate of stored CO_2 in a variety of geological formations [17].

4.3.3 Monitoring Program

Since it is possible that the stored CO_2 could leak or seep out of a reservoir, it is necessary to monitor the CO_2 via a wide range of techniques, such as 2D and 3D

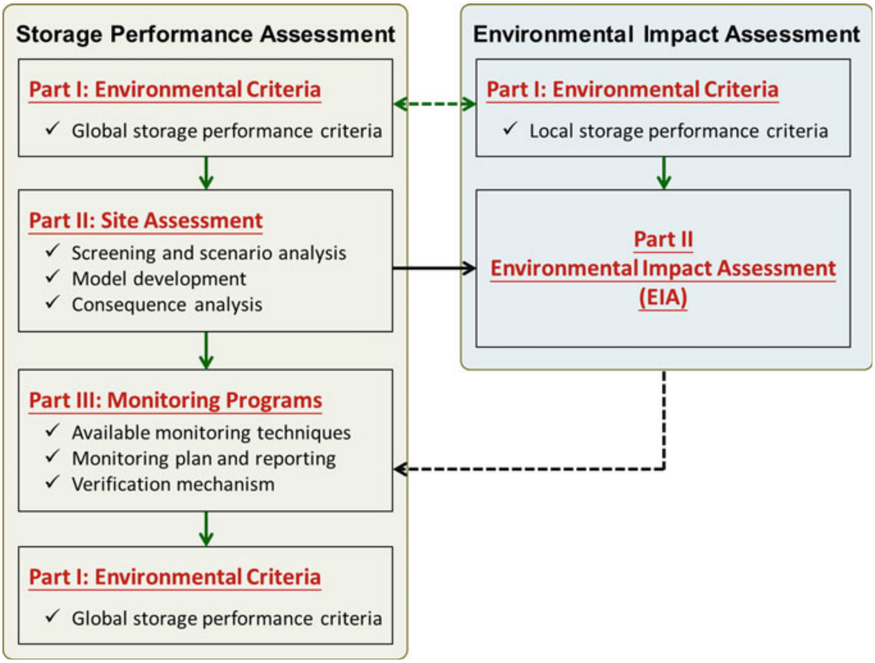

Fig. 4.3 Procedure of storage performance assessment (SPA) for EIA of a CCS project

seismic reflection surveys. Table 4.2 presents an overview of measurement, monitoring, and verification technologies for the CCS activity. Many monitoring techniques are mature but require further research and development. One of the main reasons is due to a lack of awareness of business opportunities, although industrial-scale projects usually have programs to develop and evaluate monitoring techniques. Therefore, a draft of monitoring methodology should be proposed for individual CCS projects.

4.3.4 CCS in Clean Development Mechanism (CDM)

4.3.4.1 Kyoto Protocol and Its Role in CCS Activity

Although the Kyoto mechanisms had been guaranteed by 2012, the experience in the development of these mechanisms in the Kyoto Protocol can be referred to. There are three mechanisms, i.e., (1) clean development mechanism (CDM), (2) joint implementation (JI), and (3) international emission trading (IET), included in the Kyoto Protocol:

Table 4.2 Measurement, monitoring, and verification technologies for the CCS activity (adapted from [5])

Techniques	Detection method	Technology readiness
Time lapse 4D multicomponent seismic	Acoustic	Well known
Cross well seismic tomography	Acoustic	Well known
Vertical seismic profiling	Acoustic	Well known
Down hole microseismic	Acoustic	Developmental
Electrical resistance tomography	Electrical	Developmental
Electromagnetic induction tomography	Electrical	Prototype
Soil gas sampling	Chemical	Well known
Noble gas tracing	Chemical	Early testing
Other gas tracing	Chemical	Early testing
Well head detectors	Chemical	Prototype
Brine sampling	Chemical	Well known
Subsurface and surface tilt meters	Physical	Developmental
Airborne hyper-spectral imaging	Optical	Developmental
Space-based monitoring	Microwave	Proposed

- Clean development mechanism (CDM): An incentive for companies in industrialized countries to invest in eligible emission reduction projects in developing countries.
- Joint implementation (JI): An incentive for companies in industrialized countries to reduce emissions through cooperative efforts, where a JI project may be involved.
- International emission trading (IET): Industrialized countries are allowed to meet their commitment via buying or selling excess emission credits among themselves.

Both the CDM and JI schemes are related to the project level, where introducing EIA as a set standard could be possible. In contrast, IET is related to a trading system at the international level, where EIA might possibly become a decision tool in it. Therefore, it is not anticipated that a CCS project would be accepted under the CDM and/or JI schemes without an EIA [5].

Appropriate amendments to CCS project activities should be applied under the CDM. It is noted that the CDM registry should be used to ensure the accurate accounting of the issuance, holding, transfer, acquisition, and cancellation of certified emission reductions (CERs) from CCS project activities under the CDM. In the project design, the project participants should clearly document the liability obligations arising from the proposed CCS project activity or its geological storage site [9].

According to the suggestion by the United Nations Framework Convention on Climate Change (UNFCCC), three major phases are recommended in proximity to the proposed CCS project or activity [9], including (1) characterization of suitable geological storage sites; (2) risk and safety assessment; and (3) monitoring and numerical modeling. Brief illustrations regarding CCS in the CDM can be found as follows:

4.3.4.2 Characterization of Suitable Geological Storage Site

Under the proposed conditions of use, geological storage sites should only be used to store carbon dioxide if there is no significant risk of seepage, environmental impact, and/or human health concerns. Typically, the geological storage site should not be located in international waters. Geological storage of CO_2 should be carefully evaluated to select a suitable storage site under the CDM. Available evidence (e.g., data, analysis and history matching) should be provided to indicate a complete and permanent storage of CO_2 [9], including

- Characterization of the geological storage site architecture and surrounding domains, such as
  - Structure of the geological containment
  - Areal and vertical extent of the site
  - Cap rock formation(s)
  - Overburden
  - Secondary containment zones
  - Fracture system
  - Fluid distribution and physical properties
  - Injection formation (associated with storage capacity)
- Characterization of dynamic behavior, sensitivity characterization, and risk assessment.
- Establishment of a site development and management plan (site preparation, well construction, injection rates, operating and maintenance programs, etc.).

As a result, a wide range of data and information should be collected and used in performing the characterization and selection of a suitable geological storage site. The timing and management of the closure phase of the CCS activity, including site closure and related activities, should also be addressed.

4.3.4.3 Risk and Safety Assessment

To assess the integrity of the geological storage site and potential impacts on human health and ecosystems, a thorough and comprehensive risk and safety assessment should be carried out. In this phase, the risk and safety assessment should be used to reveal the environmental and socioeconomic impact assessments of the sequestration activity. Therefore, the entire CCS chain, such as surrounding environments, should be taken into consideration and assessment. Also, it can be used to determine operational data for the application of development and management plans for the storage site. As a result, for example, the appropriate maximums of injection pressure that will not compromise the confining cap rock formation(s) and the overburden could be set.

Several key components of risks and effects should be especially considered in conducting risk and safety assessment [9, 15]:

- Containment failure: This results in emissions of greenhouse gases from above-ground installations and/or seepage from subsurface installations, thereby causing potential effects on (1) underground sources of drinking water, (2) the chemical properties of seawater, (3) human health, and (4) ecosystems.
- Continuous slow seepage from a geological storage site: It might arise due to seepage (1) along injection wells or abandoned wells; (2) along a fault or fracture; (3) through the cap rock formation; and/or (4) across faults and ineffective confining layers.
- Sudden mass release of CO_2 from surface CCS installations: it might arise due to pipeline rupture.
- Potential induced seismicity or other geological impacts.
- Other potential consequences for the environment, local ecosystems, property, and public health.

With risk and safety assessment, it could be used to help prioritize locations and approaches for enhanced monitoring activities [9]. Typically, a risk assessment comprises of four steps:

- Step 1: Hazard characterization:
  - Potential hazards resulting from the CCS activity
  - Potential seepage pathways from the geological storage site
  - Critical parameters affecting potential seepage and its magnitude
  - Sensitivity to various assumptions
- Step 2: exposure assessment:
  - Characteristics of surrounding populations and ecosystems
  - Potential fate and behavior of any seeped CO_2
- Step 3: effects assessment:
  - Sensitivity of species, communities or habitats linked to potential seepage events identified during the hazard characterization
  - Effects of elevated CO_2 concentrations in the atmosphere, biosphere, and hydrosphere
- Step 4: risk characterization:
  - Safety and integrity of storage site in the short-, medium-, and long-term scale
  - Risk assessment of seepage under the proposed conditions of use in development and management plan

Furthermore, a contingency plan for large incidents (such as seepage) should be prepared with all the necessary plans, including availability of (1) a team, (2) trained personnel, (3) materials and equipment, and (4) financial means to mitigate the adverse impacts of the large incidents.

4.3.4.4 Monitoring and Numerical Modeling

Monitoring of CCS project activities is essential to meet the following goals [9]:

- To determine the reductions in anthropogenic emissions by sources of GHGs that have occurred as a result of the registered CCS project activity.
- To provide assurance of the environmental integrity and safety of the geological storage site.
- To ensure that good site management is taking place, taking account of the proposed conditions of use set out in the site development and management plan.

In this phase, the monitoring task forces should be carried out to meet the following four objectives [9]:

- To ensure that the injected CO_2 is well contained within the storage site, as well as the project boundary.
- To confirm that injected CO_2 is behaving as predicted to minimize the risk of any seepage or other adverse impacts.
- To detect and estimate the flux rate and total mass of CO_2 from any seepage.
- To determine whether timely and appropriate remedial measures have been carried out in the event of seepage.

Typically, monitoring of the geological storage site begins before injection activities commenced to ensure adequate time for the collection of any required baseline data. The parameters and information that are monitored and collected should be transparently specified. The location and frequency of the application of different monitoring techniques during the operational phase, closure phase, and post-closure phase should also be determined. At an appropriate frequency, several key items of monitoring techniques and measurement targets include [9] the following:

- Geological, geochemical, and geomechanical parameters, such as fluid pressures, displaced fluid characteristics, fluxes, and microseismicity
- CO_2 stream and its composition at various points in the entire CCS chain
- Temperature and pressure at the top and bottom of the injection well(s) and observation well(s)
- Parameters in overburdened and surrounding domains of storage site, e.g., groundwater properties and soil gas measurements

- Detection of corrosion or degradation of the transport and injection facilities
- Effectiveness of any remedial measures taken in the event of seepage

To improve the accuracy and/or completeness of data and information, the numerical models used to characterize the storage site should be periodically updated by conducting new simulations using the monitored data and information. This could assist in adjusting the event of significant deviations between the observed and predicted behaviors. Therefore, it could confirm that no future seepage can be expected from the geological storage site.

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