

Guidelines for licensing CO₂ storage operations around the globe

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In January 2008, the European Commission proposed a directive on the geologic storage of CO₂ in the EU. Simultaneous to the development of the directive by the EC, the CO₂ReMoVe project, funded by FP6 and industry, wrote a draft contribution to future guidelines for licensing of CO₂ storage in saline reservoirs and depleted hydrocarbon reservoirs. This document contains detailed checklists for operators and authorities in each of the stages of a licensing procedure for a CO₂ storage operation. The draft guidelines will be updated as results from monitoring ongoing CO₂ storage operations become available. They may serve as a contribution to the regulation of CO₂ storage anywhere in the world, and may be also be of use in evaluating the EU directive in the future.

The geologic storage of CO₂ provides a key element in mitigating CO₂ emissions and contributing to the achievement of Kyoto (and successor) targets in a world where economic stability will depend on fossil fuels for the next several decades. The first step toward Europe's goal of becoming a hydrogen economy requires the manufacture of hydrogen from fossil fuels. This can potentially be done cost-effectively on a large scale without significantly reduced GHG emissions, if the resultant CO₂ can be securely stored in geological formations.

Europe has invested large research efforts in CO₂ geologic storage monitoring in a number of storage scenarios, gaining experience with industrial-scale projects (Sleipner, Weyburn), and smaller-scale pilot projects (Ketzin, K12B, Kaniöv). Two new industrial-scale geological storage projects (in Salah and Snøhvit) now provide the opportunity to build on this work. For CO₂ storage to qualify in emission trading schemes, research and development efforts are required to develop a sound basis for monitoring and verification. This will provide the assurance of long-term storage security and establish consistent site certification

guidelines for policy makers, regulators, and industry.

CO₂ReMoVe is a consortium of industrial, research, and service organizations with experience in CO₂ geologic storage. The consortium proposes a range of monitoring techniques, applied over an integrated portfolio of storage sites that will develop the following:

- 1) Methods for baseline site evaluation
- 2) Optimized suites of tools to monitor storage
- 3) New tools to predict and model long-term storage behavior and risks
- 4) A rigorous risk assessment methodology for a variety of sites and time-scales
- 5) Guidelines for best practice for the industry, policy makers, and regulators

This will encourage widespread application of CO₂ geologic storage in Europe and neighboring countries. So far, project efforts have resulted in the document "Draft Contribution to Future Guidelines for Licensing CO₂ Storage Operations in Saline Reservoirs and Depleted Hydrocarbon Fields."

This article describes these guidelines for the acquisition and utilization of a variety of geologic and nongeologic data. The guidelines start from eight phases in a licensing procedure that will be presented here. Next, the guidelines will be compared with the contents of the proposed EU directive on the geologic storage of CO₂. The recently proposed EU directive on CO₂ storage does not make an explicit reference to the licensing phases, but basic elements of a licensing procedure are common to both documents, notably the importance of comprehensive and robust site selection.

While the draft contribution to future guidelines contains detailed checklists for operators and authorities in each of these stages, this paper will provide brief descriptions of each

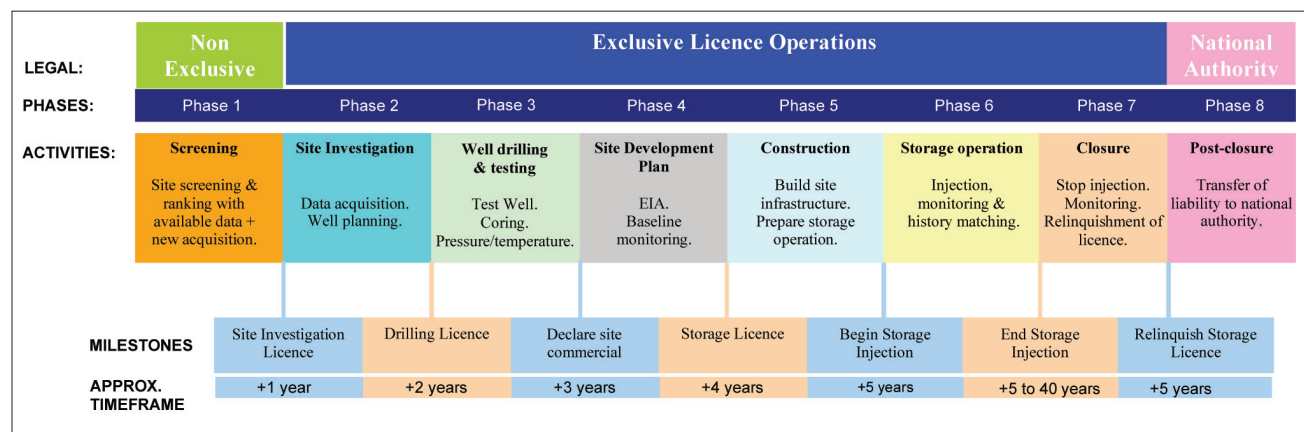


Figure 1. Phases in the realization of a CO₂ storage operation.

of the stages with reference made to the stipulations in the proposed EU directive on CO₂ storage. The article ends with conclusions on the future of both the guidelines and the EU directive on geologic storage.

Phases in a storage operation and licensing procedure. An overview of the key stages in a licensing procedure is given in Figure 1, with a brief summary of the activities associated with each phase. A CO₂ storage operation typically commences with a screening of candidate sites (Phase 1), an investigation of the selected site (Phase 2), including well drilling and testing (Phase 3), and the preparation of a site development plan (Phase 4). After these phases, the operator could be granted a site storage license, or alternatively, the licensee may walk away from a project at any time with no further obligations specific to the storage of CO₂. After the issue of this license however, the licensee will be obliged to follow the authorized site development plan for injection, storage, site closure, and associated monitoring. This entails construction (Phase 5), the storage operation (Phase 6), and site closure (Phase 7). The last phase, postclosure (Phase 8), follows after liability for the site has been handed over to the relevant national authority.

For reasons of clarity, the parties involved in a geologic storage project are here assumed to be limited to a national regulator and a storage site operating company, or licensee. This simplification does not take into account more complex regulatory structures or other stakeholders such as the general public or environmental NGOs. Furthermore, independent third parties may have a role as well. Their participation can be anticipated if:

- CCS is accepted into an emissions trading scheme, such as the EU-ETS;
- A regulator requires third party assistance in the quality assessment of the licensee's activities.

In the event that CCS is part of an emissions trading scheme, a third party would be required for validation and verification of emissions reductions. Here validation refers to the process of ensuring an accurate estimation of emission reductions prior to injection, and verification refers to the confirmation of the stated emission reductions for a given period of injection. Both processes would be performed according to anticipated guidelines for emissions accounting in the trading scheme.

Potential storage sites may be located in areas of where geological data availability is variable, largely depending on the degree of petroleum or geothermal exploration that has been carried out in the region, and some saline aquifer storage targets may have only sparse data. In such cases, drilling and well testing may need to be carried out earlier in the evaluation process than for locations in data-rich areas. This implies that the duration of Phases 1–3 may vary significantly from site to site and that an iterative approach to data acquisition in these phases may be required.

In contrast, considerable reservoir characterization data may exist for depleted oil and gas reservoirs, including those that are candidates for enhanced oil recovery (EOR). Site investigation requirements for such sites would typically focus more on legacy issues such as the integrity of abandoned wellbores than on new data acquisition.

Phase 1: screening. The screening phase evaluates the practicality and potential of storing CO₂ in an appropriate region by identifying, assessing, and comparing possible candidate storage sites. Proper screening is a first step to a well-con-

sidered site selection, and is therefore heavily emphasized in the recently proposed EU directive on CO₂ storage. The directive also specifies that member states retain the right to determine the areas from which storage sites may be selected.

Screening is typically carried out by potential site operators who would not need to get their screening activities approved by a regulatory body at this stage in the process, as long as no new data are acquired. It is anticipated that existing data sets will be used to produce a ranked list of potential storage sites based on geologic, economic, and logistical considerations.

The screening phase will end with the application for an exclusive exploration license. (Note that a grant for nonexclusive license only may be a disincentive for costly seismic investigations in this phase.) Applications should be considered in the light of other licenses in the same geologic region since the injection at one location may affect the performance of other sites even if their license areas do not overlap. The authorities may need to ask multiple operators to apply for a cooperative license in this case or demonstrate that activity at one site will not infringe upon another site. Furthermore, it may be necessary for governments to prepare licensing rounds to manage any competition that may arise between operator companies to gain access to prime storage sites.

Potential operators of storage sites should compete on the basis of their qualifications and capacities, and the specific development plans they offer to the authorities. Potential operators may need to be prequalified to participate in licensing processes.

Phase 2: Site investigation. Phase II involves further site investigation ahead of the drilling and well testing program in Phase III. The aim is to refine preliminary storage capacity estimates made in the screening phase and to provide the geologic information necessary to show that, as far as can be discerned prior to drilling, the site will perform effectively and safely. In the event that more than one site is initially selected, it is envisaged that a single preferred site would be identified during this process. The main deliverable from this phase is the information to be included in the application for a drilling license. This information should characterize the geology of the storage reservoir and overburden as accurately as possible and include a drilling program with targets and well completion and abandonment strategies.

A reasonable description of the reservoir, caprock integrity, stratigraphy, physical properties, and geomechanical setting of the reservoir and overburden should be achievable during this phase. The key data sets for a robust characterization of reservoir and overburden will normally include 2D and/or 3D seismic surveys. 2D seismic can be used to constrain geologic structures over a large area at low resolution between survey lines, whereas 3D seismic should be used to provide more detail over the predicted storage footprint and any anticipated containment risks. The data acquired during this phase should also form the basis for predictive flow modeling of the injected CO₂ in the storage reservoir. Such flow models would then form the basis for designing baseline monitoring surveys, an injection strategy, and a monitoring program.

Baseline monitoring will need to be initiated prior to injection, though the exact timing (starting in Phase II, III, or IV) will be the responsibility of the licensee. Baseline monitoring should include characterization of the following systems over timescales that take into account seasonal

and annual variations:

Geosphere—description of the geology above and beneath the storage reservoir based on seismic data and drilling, as well as the hydrogeologic context, including groundwater flows to the surface in order to assess the potential displacement of reservoir fluids to the surface caused by CO₂ injection.

Biosphere and local ecosystems—identification and monitoring of target species, particularly in protected areas, and identification of potential migration pathways through which any groundwater systems or local terrestrial or marine ecosystems may be affected.

Background fluxes—measurement of background fluxes of CO₂ (and, if appropriate, CH₄) to avoid their inclusion in the estimate of annual emissions. Isotopic analysis of any background fluxes of CO₂ may be necessary, as this is likely to help distinguish them from the injected CO₂.

The characterization of the geosphere has been addressed in the proposed EU directive on CO₂ storage, as part of the site selection process. Characterization of biosphere and measurement of background fluxes are not explicitly mentioned in this directive, but would be part of the environmental impact assessment (see Phase 4: Site development plan).

In large saline aquifers, the long-term areal extent of a CO₂ plume over time may cover hundreds of square kilometers and the prediction of the exact location of this plume may be uncertain at this stage in the process. In such cases, the need for a flexible, evolving baseline survey should be considered in order to avoid unnecessarily expensive baseline monitoring over areas that may not ultimately be affected by CO₂ migration issues. Such a survey would aim to characterize the geosphere, biosphere, and background fluxes ahead of the migrating plume and prior to their being affected by the presence of injected CO₂.

The site investigation phase would end with the application for an exclusive drilling license. This may represent an extension of the exploration license, would typically be time limited (1–3 years) and include some minimum drilling obligations. After the completion of the drilling program, the licensee must decide whether to proceed and commit to further drilling obligations or relinquish the area.

Phase 3: Drilling and well testing. The aim of well testing is to confirm and refine the site investigation from Phase II and provide key basic data for the predictive fluid-flow modeling, estimates of storage capacity, and preliminary injection program design. Well logs, downhole fluid samples, well cuttings, and core samples from test wells are anticipated to indicate the physical properties of the reservoir, caprock, and overburden. This wide variety of data must be interpreted and resolved so that they form a consistent, integrated description of the underground. Particularly important properties are the porosity and permeability values, because these determine static storage capacity and dynamic movement of the injected CO₂. Pressure and temperature information estimated for the reservoir or measured in wells can be used in the calculation of the density of the CO₂-rich phase.

The injectivity of the storage reservoir should be evaluated by injection testing. At this stage, water or CO₂ may be used for injection, although the latter will have implications for the baseline monitoring and may need to be constrained to a maximum volume. It should be noted that the amount of information available from an injection test is dependant on its duration—tests of a few days reveal reservoir properties only close to the injection well. Care should be taken

when drilling test wells to ensure that they can be used later in the operation of a storage site, or can be properly sealed to prevent leakage.

Note that the proposed EU directive on CO₂ storage does not contain any stipulations on drilling and well testing. Drilling has been regulated in the borehole directive (92/91/EEC). After drilling and well testing, the site may be declared commercial.

Phase 4: Site development plan. In Phase 4, the operation of the CO₂ injection site will be planned in detail and as will its subsequent closure. This phase is carried out as a desk-top exercise, although additional data should be acquired as needed. Baseline monitoring will also continue during this phase.

An environmental impact assessment (EIA) will be carried out to establish the safety of the project. The EIA should draw on the results from Phases 1–3 to provide an assessment of the risks to health, safety, and the local environment, as well as a plan to manage those risks that includes a monitoring programme for the operation and closure phases (6 and 7).

During this phase, the operator needs to demonstrate that the proposed storage site can offer effective climate-change mitigation by containing the stored CO₂ for a very long period, likely to be several thousand years in duration. Therefore, geologic CO₂ storage requires specific monitoring of the geosphere and biosphere, that will be described in the monitoring program, in addition to standard practice regarding health, safety, and environmental (HSE) monitoring.

Following approval of the site development plan for the construction and operation of a storage site, the licensee will be granted a site storage license. The proposed EU directive does not require that a storage license be exclusive. Competing uses in the area such as hydrocarbon production, geothermal energy, or other CO₂ storage operations should be considered by the authority before granting the license. According to the EU directive, all applications should be reviewed by the commission, who may take competing uses into account while preparing its recommendation.

After this point, the licensee would be bound to operate the storage site according to the approved plan and timeframe. Failure to do so would violate the license terms and may provide a basis for financial compensation.

The proposed EU directive does not refer explicitly to a “site development plan,” but only to applications for CO₂ storage permits, which should contain a monitoring plan, a corrective measures plan, and a postclosure plan. The directive stipulates that proof of financial security shall be part of the permit application. In general, provisions in the proposed EU directive on CO₂ storage relating to this phase place a strong emphasis on proper site selection and characterization. Properly selected storage sites will dramatically reduce the risk of leakage. Site selection will be reviewed thoroughly by the European Commission, and a nonbinding recommendation on the storage permit applications will be given to the respective member states.

Phase 5: Construction. Baseline monitoring will need to continue during the construction of surface facilities and the drilling of CO₂ injection wells in order to achieve the longest possible timeline for the baseline data.

Phase 6: Storage operation with injection of CO₂. During the storage operation, CO₂ will be transported from its source location(s) and injected into the storage reservoir

Box 1. Elements of a monitoring program proposed by CO₂ReMoVe.

The following may be monitored to enable history matching of flow modeling:

- Injected CO₂—the mass of injected CO₂, injection pressure, temperature, and gas composition
- CO₂ inside the storage reservoir—temperature and pressure data inside the reservoir, and time-lapse imaging of the migration of CO₂ within the storage reservoir
- CO₂ outside of the storage reservoir—migration of CO₂ from the storage reservoir to other parts of the geosphere. Caprock integrity is an integral part of this monitoring target.
- Surface fluxes of CO₂—fugitive CO₂ that migrates from the geosphere to the biosphere may migrate further to the seabed or ground surface. Migration paths could include fault planes, “thief zones,” wells (active or abandoned), groundwater, and soil. Periodic investigations of the entire site, and any additional area below which monitoring and modeling suggests CO₂ is distributed, should be made to detect any unpredicted leaks.
- Groundwater—CO₂ contamination of potable groundwater reserves should be detected.
- Well integrity—abandoned wells in the vicinity of the CO₂ plume will need to be monitored for leakage.

The monitoring program should also contain descriptions of the following:

- Timing of surveys during storage operation phase—repeat time-lapse surveys will need to be performed in order to describe the evolution of the above measurements through time. The monitoring program will indicate the initial frequency of these surveys, and describe how this timing will respond to the results obtained and any unforeseen events.
- Timing of surveys during the site closure phase—monitoring will be needed to demonstrate that the evolution of the CO₂ storage site is in agreement with earlier predictive models, and thus the long-term fate of the CO₂ is well understood. Depending on the success of such history matching, the frequency of monitoring surveys may be reduced.
- Layout of surveys—this should take into account land or marine use around the site, the geologic nature of the reservoir and its depth, and the location of faults, wells, and other surface infrastructure.
- Permanent monitoring installations—examples of permanent instrumentation in wells may include geophone arrays for seismic measurements, pressure and temperature sensors or fluid sampling systems. At the surface, pads for gravity surveys, or markers for other key surveys may be installed, so that specific future surveys, if needed, can be made at accurately located points to ensure better constrained comparisons with previous data sets. Such installations allow future generations to continue monitoring, although they should only be considered where their presence does not compromise the long-term integrity of the storage system.
- Monitoring and modeling techniques—the measurement technologies and predictive flow models to be used during storage operations together with a description of how monitoring techniques will be continuously reviewed to follow the most recent successful practice.
- Detection limits and uncertainty—the sensitivity of the monitoring techniques to detecting CO₂ migration and leakage.

according to the volumes and rates specified in the site development plan.

Two key aspects of this phase are the need to evaluate the degree to which the site is performing compared to pre-

dictive models through performance assessments and to evaluate the evolving containment risks through ongoing risk assessments. Performance and risk assessments will need to be carried out at regular intervals. The frequency will be site-specific, determined by discussion with the regulator (in the proposed EU directive this is at least once a year). The results may require that operating parameters and limits stated in the original site development plan be adjusted to reflect updated understanding of the storage performance.

Various types of tools can be used to monitor the observed CO₂ plume, to history-match it against flow simulations, and to provide input to ongoing performance and risk assessments. The predictive models should be calibrated against the observations, and future predictions of plume behavior should be modified based on the calibrated history-matched models. The monitoring program (Box 1) will have been described in the site development plan (Phase 4).

Storage operation ends when the licensee ceases CO₂ storage operations for commercial or technical reasons with the approval of the authorities. Alternatively, should site performance deviate significantly from acceptable limits, the regulator may force cessation of injection.

Regulatory requirements of monitoring should not be prescriptive but should rather reflect site-specific conditions and objectives (Box 1).

The specifications in the proposed EU storage directive (presented in Box 2) diverge slightly from the requirements suggested in Box 1. For instance, the directive does not contain any stipulations on the permanency of monitoring installations. It only suggests some groups of monitoring techniques suggested, including technologies that can detect presence location and migration subsurface, technologies that can provide information about plume behavior (3D simulation in 3D models), and technologies that can provide wide areal spread (across the complete storage complex). Monitoring equipment is to be based on the best available technology at the time the monitoring plan is designed. Furthermore, the directive does not address uncertainties in the monitoring programme or detection limits. These issues are to be addressed in regulations on the accounting of CO₂ emissions from CCS operations participating in the EU emissions trading scheme. At present, a CCS annex to the 2007 EU-ETS monitoring and reporting guidelines is being developed.

Phase 7: Site closure. The closure phase of a CO₂ storage project represents the period of time between ceasing to inject CO₂ and transferring liability for the site from the licensee to the relevant national authority. The closure phase will have been planned initially in the site development plan, with possible subsequent modification to reflect the evolving performance and risk assessments. Surface infrastructure associated with CO₂ storage will be removed and injection wells should be sealed as soon as possible unless used for monitoring purposes. Indeed, the proposed EU directive stipulates that a corrective measures plan and a provisional postclosure plan should be part of the permit application.

During site closure, the operator will demonstrate that the total storage system is understood in a sufficiently detailed way so that future performance can be robustly assessed as satisfactory. Ongoing monitoring and history matching of predictive models will be required in order to provide evidence that the system is well understood and that the site may be closed. Until then, regular submission of performance and risk assessment reports to the regula-

Box 2. Site characterization, static and dynamic modeling, and contents of a monitoring plan according to the proposed EU directive on CO₂ storage.

Criteria for the characterization and assessment of storage sites, including a list of required data on characteristics of the complex:

- (a) reservoir geology and geophysics;
- (b) hydrogeology (in particular existence of potable ground water);
- (c) reservoir engineering (including volumetric calculations of pore volume for CO₂ injection and ultimate storage capacity, pressure and temperature conditions, pressure-volume behavior as a function of formation injectivity, cumulative injection rate and time);
- (d) Geochemistry (dissolution rates, mineralization rates);
- (e) Geomechanics (permeability, fracture pressure);
- (f) Seismicity (assessment of potential for induced earthquakes);
- (g) Presence and condition of natural and man-made pathways that could provide leakage pathways, as well as data on the complex vicinity.

A static geologic Earth model will characterize the complex in terms of:

- (a) geologic structure of the physical trap;
- (b) geomechanical and geochemical properties of the reservoir;
- (c) presence of any faults or fractures and fault/fracture sealing;
- (d) overburden (caprock, seals, porous and permeable horizons);
- (e) areal and vertical extent of the storage formation;
- (f) pore space volume (including porosity distribution);
- (g) and any other relevant characteristics.

Dynamic modeling shall provide insight to:

- (f) pressure-volume behavior versus time of the storage formation;
- (g) areal and vertical extent of CO₂ versus time;
- (h) the nature of CO₂ flow in the reservoir including phase behavior;
- (i) CO₂ trapping mechanisms and rates (including spill points and lateral and vertical seals);
- (j) secondary containment systems in the overall storage complex;
- (k) storage capacity and pressure gradients in the storage site;
- (l) the risk of fracturing the storage formation(s) and caprock;
- (m) the risk of CO₂ entry into the caprock (e.g., because of exceedance of capillary entry pressure of the caprock or due to caprock degradation);
- (n) the risk of leakage through abandoned or inadequately completed wells;
- (o) the point when overspill may occur (in physical traps);
- (p) the rate of migration (in open-ended reservoirs);
- (q) fracture sealing rates;
- (r) changes in formation(s) fluid chemistry and subsequent reactions (e.g., pH change, mineral formation, and inclusion of reactive modeling to assess affects);
- (s) displacement of incumbent formation fluids.

tor will continue.

The frequency of monitoring is likely to decrease with time during site closure as confidence in models increases. Clearly, if the system does not behave as predicted, such as if unexpected migration occurs or leaks develop, then the frequency and types of monitoring may increase. Thus, any residual risk can be minimized and liability can be transferred from the operator to the designated national author-

The monitoring plan shall specify:

- (a) parameters monitored;
- (b) monitoring technology employed and justification for technology choice;
- (c) monitoring locations and spatial-sampling rationale;
- (d) frequency of application and temporal sampling rationale.

The parameters to be monitored are identified to fulfill the purposes of monitoring. However, the plan will include continuous or intermittent monitoring of the following items:

- (a) fugitive emissions of CO₂ at the injection facility;
- (b) CO₂ volumetric flow at injection wellheads;
- (c) CO₂ pressure and temperature at injection wellheads (to determine mass flow);
- (d) chemical analysis of the injected material;
- (e) reservoir temperature pressure (to determine CO₂ phase behavior and state).

ity.

The duration of the site closure phase could vary significantly depending on specific site characteristics and required tolerances in matching models and monitoring data. It will end with the relinquishment of the site storage license and transfer of liability to the relevant national authority.

Phase 8: Postclosure. The postclosure phase will last an indefinite length of time, with responsibility for the storage site residing with the designated national authority. The primary safety issue of the postclosure phase is to avoid future subsurface activity that may disturb the CO₂ storage reservoir and compromise its sealing performance. Otherwise, the site has already proven its "undisturbed" storage performance during the closure phase and the national authority is in possession of the performance and risk assessment reports demonstrating long-term safety of the site.

Safety in the postclosure phase should not be based on a requirement for future monitoring, since this may be construed as placing an unethical burden on future generations to continue monitoring. Rather, the safety of the site should be based on its inherent qualities established during site selection and characterization, and confirmed by monitoring during the operational and closure phases. Observations and data collected during the injection phase and dynamic modeling calibrated to this will likely supersede and make redundant some or much of the original site selection material. These qualities include the caprock integrity, wellbore-abandonment techniques, sealing features such as faults and fractures, and operational history (injection pressures, volumes, injection point, etc.). Therefore, monitoring should not be needed in the postclosure period, only becoming necessary if unforeseen circumstances arise.

Draft CO₂ReMoVe guidelines and the proposed EU directive on CO₂ storage. In this paper, we discussed the various phases in a licensing procedure that have been described in the draft contribution to future guidelines elaborated by the CO₂ReMoVe partners. The recently proposed EU directive on CO₂ storage does not make an explicit reference to these stages, but crucial elements of a licensing procedure are included to both documents; in particular, the impor-

tance of comprehensive and robust site selection.

The proposed EU directive is not fully comprehensive. For instance, the directive does not contain stipulations on the permanency of monitoring installations, reviews of monitoring technologies, uncertainties, or detection limits. These issues are important in particular when it comes to quantifying the volume of potentially leaked CO₂. Quantification of fugitive emissions is fundamental if stored CO₂ is to have economic value in the EU (or any other) emissions trading scheme. Therefore, monitoring and reporting guidelines on accounting emissions from CCS operations are at present being developed by the European Commission.

A number of other issues that have been dealt with in the proposed EU directive are not addressed in the draft contribution to future guidelines. These include ways to guarantee a harmonized approach across countries to the evaluation of permit applications, the inspection of injection and storage operations, possible measures in case of leakage, CO₂ stream acceptance criteria, and third-party access to CO₂ infrastructures. Future updates of the CO₂ReMoVe draft guidelines could deal with these issues. Currently, work is underway to improve guidance on acceptance criteria for impurities in CO₂ streams.

Although any guidance document on licensing CO₂ storage operations will need to be evaluated and updated frequently as new insights from field operations become available, the "Draft Contribution to Future Guidelines for Licensing CO₂ Storage Operations" prepared by the CO₂ReMoVe partners offers a good start for licensing CO₂ storage operations. If it can help to assist legislators worldwide in elaborating effective and reasonable regulations for CO₂ storage operations, it will have met its purpose. [TjE](#)

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