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Safety criteria for CO_2 geological storage: determination workflow and application in the context of the Paris Basin

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Abstract

For carbon dioxide capture and storage to make an effective contribution in reducing greenhouse gas emissions, a large number of storage sites will be required. Safety will have to be demonstrated for each of these sites. We present in this paper a simple and flexible framework to assess safety of a CO_2 storage site in a time-efficient manner. It includes the identification by an expert panel of the relevant risk scenarios. Their evaluation privileges analytical or semi-analytical modelling with conservative assumptions. Uncertainty is managed in order to thoroughly represent and propagate the nature of information relative to the site properties. We illustrate the application of this framework with a case study in the context of the Paris Basin. The workflow described is not a complete risk assessment framework, but it constitutes a useful tool for an operator at an early stage of a project or to iteratively screen safety issues, or for a regulating authority to review the safety conditions of a project.

Keywords: CO_2 geological storage; safety; risk; uncertainty; assessment method

1. Background and objectives

Anthropogenic greenhouse gas emissions should be reduced to mitigate climate change and ocean acidification. This effort requires adopting a number of measures, especially improving energy efficiency and increasing the share of renewables in the energy mix. According to the International Energy Agency [1], Carbon dioxide Capture and geological Storage (CCS) may contribute up to 20 % to this effort by 2050. For this technology to have an effective impact on emissions reduction, the agency estimates that 100 projects should be implemented worldwide by 2020 and more than 3000 in 2050 [1]. To achieve such a large number of projects, it is essential to be able to demonstrate both effectiveness and safety of each of them. This concern constitutes the rationale for the recently issued European

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Directive on CO_2 geological storage [2], which "establishes a legal framework for the environmentally safe geological storage of carbon dioxide".

In prior work [3], we have underlined why CO_2 storage needs an innovative framework for assessing risks compared to other applications such as industrial risk analysis: in particular, CCS faces unusual time scales and significant uncertainties. Risk assessment for CO_2 storage has thus constituted a research topic. So far, various approaches have been used but none of them has been widely recognised as a standard.

The research reported here aims at establishing a simple and flexible framework to identify the major conditions to ensure that a CO_2 geological storage site is safe. This is to say that it should have negligible impacts on human health and safety, on the environment or on underground resources, both in the short and in the long term. Not a complete risk assessment framework, the proposed approach is meant to provide safety evaluation elements in a time-efficient manner, encompassing all kinds of safety-related risks associated with CO_2 storage. It should accommodate qualitative and quantitative data, so that it could be run with various levels of knowledge.

We thus adopted simple tools for identifying and assessing risk scenarios and for handling uncertainty. As many of these tools have already been addressed in previous publications, we only briefly introduce them in the following. Then we present the workflow to use such models to determine safety criteria, and we exemplify its application in the context of the Paris Basin.

2. Risk scenarios identification and modelling tools

Looking for a simple framework, we foster generic tools that can be run in a time-efficient manner. In particular, time-efficient computation of the models for representing risk scenarios allows assessing uncertainty. Rather than an accurate output, we are expecting order of magnitude results informing safety assessment. We thus try to apply analytical or semi-analytical models, to the extent possible, rather than detailed site-specific numerical models. To this end, simplifying assumptions are needed. In a precautionary approach, such assumptions are taken conservative. In this process, avoiding over-simplifying is a concern, since the framework should not be overly conservative.

2.1. Risk scenarios identification

According to the CO_2 storage Directive [2], the expected behaviour of a storage site is that CO_2 should be permanently contained; no significant leakage risk and no significant health or environmental risk should exist. Safety assessment must identify and evaluate potential deviations from this reference scenario. For determining the risk scenarios that have to be studied, given the specific conditions of the investigated site, we apply the approach described in [3] and inspired by [4]: an expert panel selects among a generic short list the risk events that have to be considered, on the basis of its knowledge of the site, and the potential assets at stake.

2.2. Main modelling tools for representing the behaviour of a CO_2 storage site

A simple evolution model in the reservoir is provided for CO_2 in [5] and for the pressure field in [6]. Thus the extent of the CO_2 plume and the pressure behaviour during the injection phase can be computed for the reference scenario.

We developed a semi-analytical model for studying mechanical integrity failure of the cap rock [7]. It delivers charts from which, given the geometrical, mechanical and petrophysical properties of the site, the maximum sustainable pressure can be readily deduced.

An analytical model has been proposed for studying CO_2 entry into and rise through an abandoned well [8]. For CO_2 migration out of the storage formation through a porous medium (fault, permeable zone), we use an analytical one-dimension biphasic Darcy flow model, that was validated against numerical simulations using the TOUGH2 [9] software.

2.3. Uncertainty management

As we underlined it in [3], a thorough management of uncertainty should distinguish between *stochastic uncertainty*, which relates to the natural variation of a parameter over time or space, and *epistemic uncertainty*, which relates to an incomplete knowledge of the scientist with respect to the studied feature. To avoid introducing subjectivity prior to the decision-making stage, it is required to:

- faithfully represent the available information;
- jointly propagate both kinds of uncertainties along the computation.

We have established a flowchart enabling the choice, for a parameter, of a mathematical representation appropriate to the nature of available information [10]. The corresponding tools come from probability theory or other uncertainty theories such as possibility theory, evidence theory, and imprecise probability (see [**Erreur ! Source du renvoi introuvable.**] for a bibliography). Dubois and Guyonnet [10] then present how to propagate the information while remaining faithful to its nature, and how to exploit the outcome of this process for decision-making. In presence of epistemic uncertainty, a pair of lower and upper probability bounds can typically be derived from the outcome of the uncertainty propagation, the "actual" probability distribution lying somewhere in between these two curves. As this kind of result is not easy to exploit for decision-makers, it is suggested to refer to a weighted average of these two bounds, the pessimistic bound being awarded a heavier weight in a precautionary approach. This average is termed "confidence index" [10]. The weighing coefficients should be set with the decision-maker depending on the context; values of 2/3 for the pessimistic bound, 1/3 for the optimistic one are suggested as reasonably conservative [10].

2.4. Impact assessment

For assessing safety, potential impacts resulting from the various risk events have to be estimated. In the case of a CO_2 release, past studies ([12], [13]) noticed that the effects on terrestrial ecosystems are poorly known. Consequently, we focus on two assets: impacts of a CO_2 release at ground level on human health, which are relatively well understood, and impacts of a release into freshwater aquifers, which would chronologically be the first assets affected.

2.4.1. Impact of CO_2 leakage on human health at ground level

Effects of elevated atmospheric content of CO_2 on human health are fairly well documented. Exposure thresholds in the French regulation are given in Table 1. For converting CO_2 flow rates delivered by the release models into CO_2 atmospheric content, we use a rough model similar to the one described in [14]. A release pathway is assumed to open right under a building; a simple dilution computation delivers the CO_2 content in the indoor atmosphere. Assuming typical parameters for a house ([15]) and its ventilation rate (0.5 air change per hour [16]), the limit release rates associated to the regulatory exposure thresholds are reported in Table 1.

Table 1 French regulatory thresholds for CO_2 exposure and associated release rates according to the simple indoor exposure model

Threshold	8-hour average occupational exposure	Short-term exposure	First lethal effects	Significant lethal effects
CO_2 content (% vol)	0.5	5	10	20
Release rate into a house ($g.s^{-1}$)	0.3	3.4	6.8	13.6

2.4.2. Impact of CO_2 leakage on freshwater aquifers

CO_2 intrusion into a freshwater aquifer would locally decrease the pH of water, hence disturbing the chemical equilibrium of the water-rock system. Vong [17] and Jacquemet [18] describe reactive transport simulations carried out to assess subsequent impacts on water quality. They study an aquifer derived from the characteristics of the Albian aquifer in the Paris Basin and respectively consider pure CO_2 intrusion and a CO_2 stream charged with associated substances dubbed "impurities".

Such modelling shows water quality alteration in a volume around the intrusion zone. The nature and magnitude of chemical changes and the extent of the domain where they occur are highly dependent on the initial state of the water-rock system. The aquifer's mineralogy determines the elements present in the system that are sensitive to dissolution or precipitation. The assessment of the effects of the CO_2 stream intrusion is therefore highly site-specific. It does not seem feasible to draw any generic conclusion on the impacts of a CO_2 release into a freshwater aquifer, nor to establish a generic threshold release rate above which impacts are significant. Numerical modelling on a case-by-case basis is recommended to assess these effects.

3. Proposed workflow

The workflow we propose for assessing safety for a CO_2 geological storage project is sketched on Figure 1. It combines six steps:

1. Data relative to the investigated site(s) is gathered and integrated into a Geographical Information System (GIS). Depending on the context of the assessment and the level of knowledge of the site, it can be supplied from a literature review or from field measurements, and be more or less detailed.
2. The expected behaviour of CO_2 and pressure in the reservoir is computed with the analytical models described above, assuming injection through a single well. This constitutes the reference scenario. Taking into account uncertainty pervading the reservoir properties, we suggest, at this early step of the assessment, to adopt the most pessimistic estimate to determine the maximum possible extent of the CO_2 plume, in order to be as comprehensive as possible for identifying potential risks.
3. Based on the GIS, the simulation results for the expected behaviour of the storage and the generic events and assets lists, an expert workshop identifies potential deviations from the reference scenario that have to be assessed in the context addressed. They constitute the relevant risk scenarios.
4. For each of these scenarios, assuming it occurs, simulations are performed to evaluate the magnitude of the relevant phenomenon. This resorts to the extent possible to the simplified risk events models described above. It takes as inputs the outcomes of the simulations for the reference scenario as well as properties (or assumed range of properties) of the considered features. For instance, the potential CO_2 flow rate out of an abandoned well is estimated using the analytical "well leakage" model, depending on the permeability and thickness of the well seals, and based on the probability of presence of CO_2 and pressure at the basis of the well, as delivered by the expected behaviour models. At this stage, we suggest to refer to the confidence index for establishing reasonably conservative estimates. When no generic model exists, then a specific numerical model should be built. Qualitative judgement may complement this step for some events in the absence of sufficient quantitative information.
5. In parallel with the previous step, evaluation criteria need to be established, given existing regulatory thresholds. These criteria can be defined by the user with respect to the context and decision stakes. The impacts assessment models can be applied to establish a threshold CO_2 leakage rate, as presented above; for mechanical integrity of the cap rock, we suggest to use a "no rupture" criterion.
6. For each of the risk scenarios, simulation results are compared to the evaluation criteria. Then this process discriminates settings that are proven safe from those which are not. However, since the whole workflow is designed conservatively, it does not deliver necessary conditions but only sufficient conditions. A setting that fails to pass the evaluation step may be safe anyway; it is just not proven safe.

Then failure to pass the evaluation may result from several grounds; accordingly several follow-ups may be needed:

- Failure may be the consequence of too restrictive models; a new assessment may then be carried out using a similar workflow with more elaborate models.
- It may result from a too high level of uncertainty; then additional data should be acquired through a literature review or a characterisation campaign.
- There may really be safety issues with the considered site in its proposed conditions of use; then the operational design should be modified, including for instance changes in the injection position or strategy, or implementation of risk prevention measures.

Obviously these sources of failure may be combined, and it might be tricky to distinguish their respective weights.

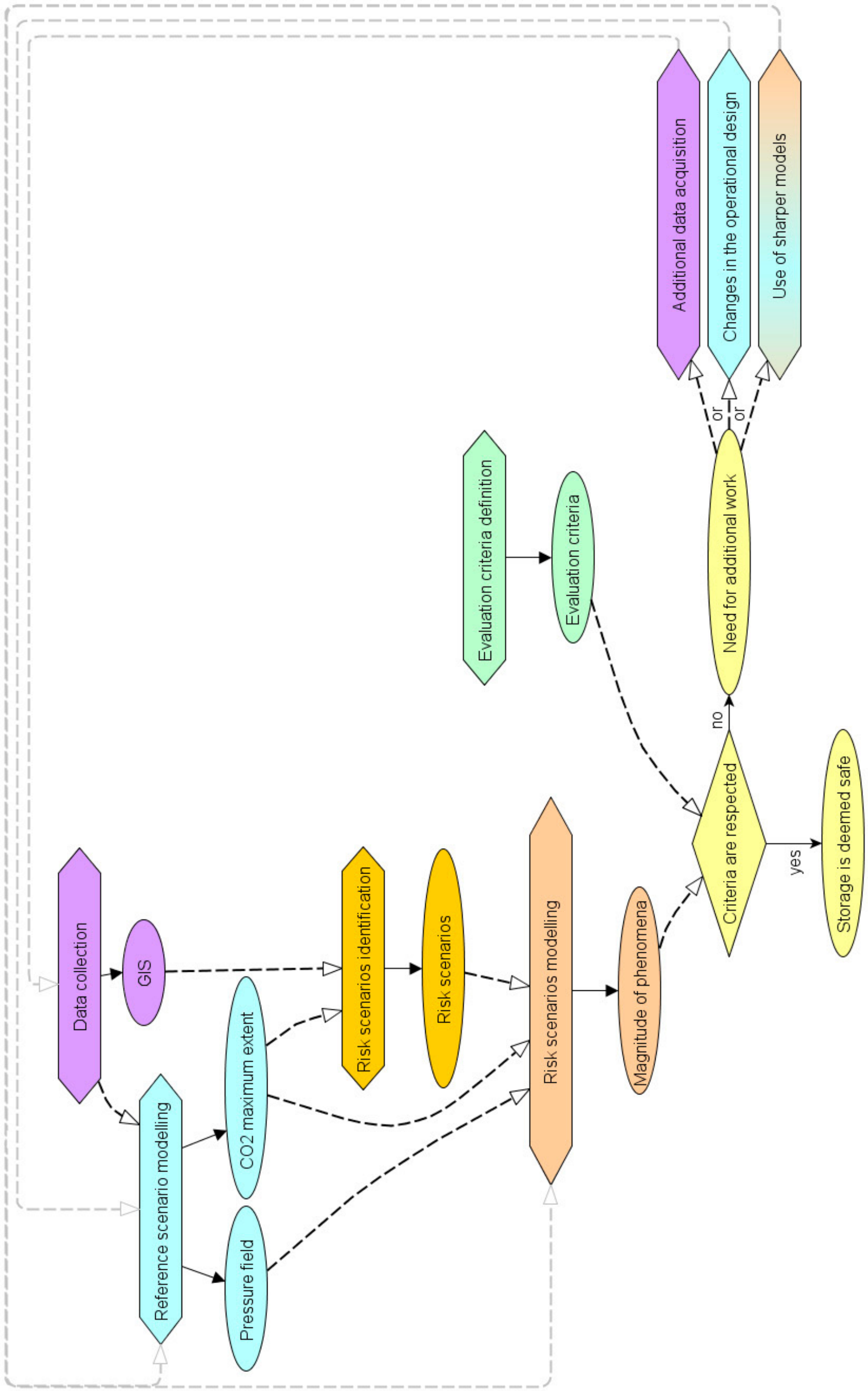

Figure 1 Proposed workflow

4. Case study

The proposed workflow has been applied on a hypothetical case study in the Paris Basin, about 100 km east of Paris. The considered sector, reported on Figure 2, was investigated for CO_2 storage in the PICOREF project [19]. Two areas were identified in [20] for injection of CO_2 into the Dogger limestone aquifer, laying at about 1500 m depth in this sector. We arbitrarily chose an injection point in the eastern area.

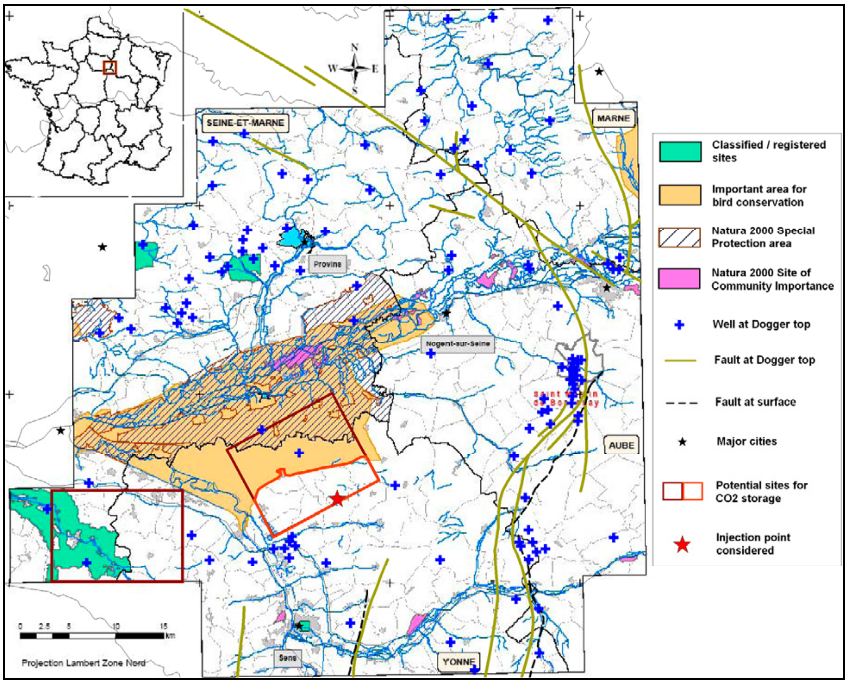

Figure 2 Case study sector in the Paris Basin, after the PICOREF project [20]. Map showing potential storage areas identified in [20], the assumed injection point, faults and wells reaching the Dogger formation and some of the environmental constraints at ground level.

Assuming 20 years pure CO_2 injection at 5 $Mt.yr^{-1}$, the analytical model for CO_2 flow in the reservoir delivers, as pessimistic bound, a 14.8 km CO_2 extent at the end of the injection period. With this data, an expert workshop judged that most of the 11 risk events listed in [3] had to be dealt with: only the potential for natural seismicity in the sector was excluded, and the potential for a future drilling into the storage formation was considered the responsibility of the operator of this future activity.

Using the confidence index with weighing coefficients of 2/3-1/3 in a reasonably conservative approach, we find that 11 wells attaining the Dogger top and one fault, located 8.4 km south-south-east of the injection point, could be reached by the CO_2. Each of these objects is studied using the appropriate analytical model. For instance, the 3 closest wells are located 6.2 km from the injection. A release through one of them would remain below the threshold rate established in Table 1 for occupational exposure (0.3 $g.s^{-1}$) as soon as a well plug is present with a ratio thickness over permeability over $2.10^{16} m^{-1}$. That is to say, if it can be shown that each of these wells is plugged with 2 m of cement which permeability will durably remain below 0.1 mD (10^{-16} m²), or 20 m of cement below 1 mD (10^{-15} m²), then these wells do not represent a threat to human health. A release through the fault would not either cause an excessive occupational exposure as soon as the product of the fault's permeability and its section in surface within a 100 m² area (corresponding to the surface area of the reference house in our exposure model) is smaller than $6.6.10^{-15}$ m^4; this would for instance be the case, over 10 m length, for a 1 m wide fault zone with an effective permeability equal to 0.5 mD (5.10^{-16} m²).

The charts provided in [7] show that, in the conditions of this case study, a 1.7 ratio between the overpressure resulting from CO_2 injection and the initial reservoir pore pressure is sustainable with respect to the cap rock tensile fracturing. The shear slip fracturing mode requests additional characterisation of the internal friction angle and the initial stress state ratio. If they are respectively greater than 30° and 0.6, the level of overpressure mentioned above is also sustainable with respect to the cap rock shear slip fracturing. An injection overpressure as high as 1.7 times the initial pressure, *i.e.* equal to 27 MPa, thus appears acceptable with regards to cap rock mechanical integrity.

In this hypothetical case study, the other risk scenarios cannot be quantitatively addressed with our simple modelling tools. Some risks could be assessed in a qualitative way; for instance CO_2 leakage through the injection well should be prevented by adopting the best available techniques for drilling and completing the well. Other scenarios, such as hydrodynamic impacts on overlaying aquifers due to pressure changes in the reservoir, could be studied through site-specific numerical modelling.

5. Discussion and perspectives

The workflow described on Figure 1 appears fairly generic and can be followed with every kind of tools for performing each of its steps. We chose to use simple tools whenever possible, but this workflow is flexible; it could be carried out with a series of more complex numerical models.

Using simple tools presents several advantages though. First it allows time-efficient performance of the workflow. Our case study is representative of a site with limited knowledge, since literature data has been collected but no field exploration has been conducted. The application on this case study shows that the framework is suitable to such a site; obviously it could also accommodate more data. A time-efficient framework then gives the ability to perform an assessment at various stages of a project, with various levels of knowledge. The proposed framework could also be used to the benefit of a competent authority for reviewing in an application whether and how the main risks have been addressed. Second, time-efficient simulations allow the computation of uncertainty propagation. Though uncertainty relating to the models themselves is usually larger when the models are made simpler, the influence of uncertainty pervading the parameters can be clearly depicted. Thus the results can inform a characterisation program by ranking the parameters according to the value of acquiring more data about them.

The proposed framework does not constitute a complete risk assessment method, since it does not incorporate a probability for the various risk scenarios. A probability for CO_2 to reach a potential release pathway can be derived from the uncertainty propagation in the computation of the CO_2 flow in the reservoir. However, it does not represent a probability of occurrence of the CO_2 release scenario, since a “failure” probability should be taken into account (in this case, the probability for the pathway to effectively be conductive).

Perspectives for this work include improving the treatment of long term issues. For the reference scenario, only the injection phase can be adequately represented by analytical models; long term behaviour of CO_2 in the reservoir is only computed through numerical simulations. A way forward could consist in comparing numerical simulations results over the long term to analytical outcomes at the end of the injection period, and to examine the feasibility of extrapolating the latter to evaluate the former.

The assessment of impacts should be improved as well. The exposure model for human should be refined and made less conservative. More knowledge on the effects of elevated CO_2 exposure on ecosystems is required to satisfyingly take into account potential impacts of a CO_2 release on fauna and flora. The effects of substances associated to CO_2 in the released stream may also be more stringent and should be further investigated.

Risk scenarios considered here are relatively simple; potential combinations between them should be examined to take account of simultaneous occurrences or accidental sequences. Finally safety assessment is only one component in a risk management framework. To adequately manage risks, it should be completed with a monitoring programme and a preventive and corrective measures plan. The last two gaps are currently being addressed: Le Guénan *et al.* [21] are in the process of building a generic database detailing the potential combinations of risk events and associating them the risk mitigation measures available in the literature.

6. Conclusion

We have described a simple and flexible framework to assess safety of a CO_2 storage site. Using analytical or semi-analytical models to the extent possible, it can be performed in a time-efficient manner to deliver a conservative assessment of the safety conditions for a site, considering all kinds of risks related to safety of a storage site. It incorporates an uncertainty management approach to remain faithful to the nature of information, and it accommodates various amounts of data. The framework is also flexible to changes of tools for conducting each of its steps, so that more complex models can also be adopted. Though not a complete risk assessment framework, it constitutes a useful tool for an operator at various stages of a project, especially the early ones, or for a regulatory review of the safety of a project. The next step consists in integrating this work into a broader risk management scheme, incorporating monitoring as well as preventive and corrective actions.

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