Executive Summary EU FP7 MiReCOL

CO_2 storage projects must develop a corrective measures plan (CMP), as part of the application for a storage license. This plan describes the measures that can be taken if the behaviour of the CO_2 in the subsurface does not conform to expectations. The EU FP7 MiReCOL project (2014-2017) has investigated a wide range of potentially useful methods to correct, or mitigate the effects of, undesired CO_2 migration, focusing on application in the deep subsurface, within or close to the storage formation. The point of view was that correction or mitigation close to the origin of the cause could be more effective than near the surface, where the CO_2 is likely to have become dispersed and difficult to detect. The MiReCOL project aims to extend the range of options open to CO_2 storage site operators to remedy or mitigate non-conformance in the reservoir.

Three classes of causes for the non-conformance were considered, each with a range of corrective measures.

1. *Loss of conformance in the reservoir.* This can be due to reservoir compartmentalisation / discontinuity (leading to unexpected increase of injection well pressure), spread of the CO_2 plume beyond the desired region (e.g. spread beyond the spill point). Corrective measures considered include injection of gels or foams, a change of injection strategy, or injection or withdrawal of brine to create a competitive fluid movement.
2. *Natural barrier breach, referring to migration of CO_2 or displaced brine through seals, faults or fractures.* The feasibility of reducing or interrupting leakages through faults and fracture networks was considered by assessing several ways of managing faults or fracture or the properties of faults.
3. *Well-related non-conformance.* The oil and gas industry has a best-practice portfolio of remediation technologies in place, which is also applicable to CO_2 injection wells. New developments and emerging technologies were considered in the project, including gels, smart cement and polymer resins. A field test was held at the Serbian Bečej natural CO_2 field, where the effectiveness of a CO_2-reactive suspension to seal the well was demonstrated.

Delivering the results: supporting the CO_2 storage site operator

A portfolio approach to corrective measures was developed, which can help set up corrective measures plans. Key performance indicators (KPIs) were defined for each corrective measure: timescale to effective cessation of leakage, longevity of remediation, likelihood of success, economic cost, environmental impact at the surface, location of retention of the CO_2 (i.e. within reservoir, within storage complex etc.). To improve the applicability of the project results and help clarify options open to site operators, a web-based tool was developed that evaluates these KPIs for each corrective measure, for a non-conformance case defined by the user. This provides insight in the applicability or relevance of corrective measures for the user-defined cases. In this way, the tool supports site operators to create a corrective measures plan for their site, and supports competent authorities to understand the options that are open to site operators in case of non-conformance.

The results from the MiReCOL project support the development of corrective measures plans and help build confidence in the safety of deep subsurface CO_2 storage by providing a toolbox of techniques to mitigate and/or remediate undesired migration of CO_2. The MiReCOL reports, as well as the corrective measures web tool, can be accessed through www.mirecol-co2.eu.

Project context and main objectives EU FP7 MiReCOL

CO_2 capture, transport and storage (CCS) has the potential to significantly reduce the carbon emission that follows from the use of fossil fuels in power production and industry. In Norway, integrated full-scale projects are operational (Sleipner, Snohvit); in the rest of Europe, full-scale projects operating in Europe under the Storage Directive have not yet advanced beyond the drawing table, but have already shown the technical feasibility of full-scale CCS. For the license applications of these projects a corrective measures plan is mandatory, describing the measures to be taken in the unlikely event of CO_2 leakage. Past projects, particularly onshore, clearly brought to light public opposition to geological storage of CO_2, arising for a large part from a negative perception of the safety and security of storing CO_2 in the deep subsurface. The MiReCOL project aims to support the construction of such corrective measures plans and help building confidence in the safety of deep subsurface CO_2 storage, by laying out the toolbox of techniques available to mitigate and/or remediate undesired leakage of CO_2. The MiReCOL project is particularly aimed at (new) operators and relevant authorities.

The Storage Directive requires an exhaustive characterisation of the storage complex, to ensure a location is selected, where it is extremely unlikely that the CO_2 will escape from the reservoir. Proper site design and injection strategies minimise the risk of leakage and a monitoring program is required to closely monitor those areas in the storage system where the residual risk of leakage, although small, is highest.

Safe and secure long-term storage of CO_2 requires the ability to detect, characterise, mitigate and remediate unexpected migration or leakage of CO_2 both inside and out of the storage complex. A clear description and understanding of the options for mitigation and remediation of leakage will help change the negative associations with CO_2 storage that currently make it difficult to develop demonstration projects.

The EU Storage Directive (2009/31/EC) establishes "*the obligation on the operator of the storage site to take corrective measures in case of leakages or significant irregularities on the basis of a corrective measures plan submitted to and approved by the competent national authority*". Corrective measures are defined in the EU Storage Directive as (Article 3.19) "*any measures taken to correct significant irregularities or to close leakages in order to prevent or stop the release of CO_2 from the storage complex*". These elements of the Storage Directive, together with the call text, define both the starting point and the scope of the project.

The starting point for the MiReCOL project is a storage site in the operational or post-operational phase, i.e., a storage site in which injection of CO_2 is ongoing or has been completed. This implies that all the necessary licenses are in place, that all risk mitigation measures have been taken and that a suitable and effective monitoring system has been installed. At some point during the project, a *'significant irregularity'* occurs. It is at this point that the results from MiReCOL apply.

The scope of MiReCOL therefore includes those corrective measures that can be applied *after* a significant irregularity is detected, in any part of the storage complex. This includes the reservoir and cap rock, the overburden, the wells and the (near-) surface. This scope therefore covers all leakage scenarios mentioned in the call. The figure illustrates this in a bow-tie representation of feature-event-processes (FEP) combination.

Once a significant irregularity has been detected, the operator will increase monitoring efforts to define the size and assess the impact (risk) of the irregularity. Following the Storage Directive, the threat to human health and to the environment must be assessed (in case of a leakage), or the probability that the irregularity will lead to a leakage event. The next step is to assess the options of taking corrective measures. The operator, in close contact with the competent authorities, will assess the impact and risk of each option to evaluate whether its deployment is viable.

Central to this project is the notion of risk level. While a 'significant irregularity' may signal a threat to the safety and security of storage, the decision to take action should depend on both the unmitigated risk and the mitigated risk. The former represents the risk associated with the unexpected behaviour of CO_2 that is detected in the subsurface, without any corrective actions taken. The latter is the risk associated with the storage complex after applying the corrective or mitigation measure. A corrective or mitigation measure could completely seal a leak and neutralise the volume of leaked CO_2, but its effect on the safety and security of storage could be such that the total risk after remediation would be higher than before. As an example, a pressure relief well affects the integrity of the cap rock, which may represent a higher risk than an unexpected migration of the plume of free CO_2 in the reservoir.

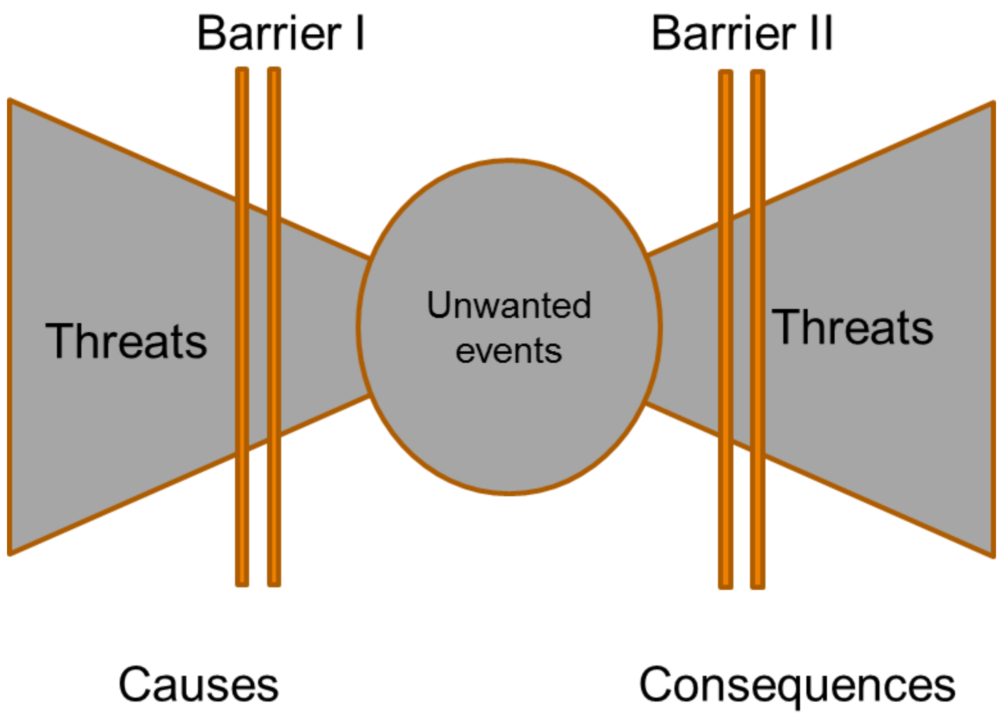


Figure 1: bow-tie representation of threats (left side), events (in the centre) and consequences or calamities (right-hand side. Mitigation and remediation measures, the subject of MiReCOL, are represented by both Barrier I and Barrier II.

All remediation and mitigation measures considered in the project were studied from all angles, to investigate their impact on all levels of risk. This will:

- provide the information that will allow operators to assess the absolute and relative values of mitigation measures;
- help competent authorities understand the options open to CCS storage operators;
- inform the local authorities about available options to mitigate or remediate in case of leakage to the (near-) surface or atmosphere.

It is has been noted many times in the literature that the safety and security of storage is highly site specific. This is also true for mitigation and remediation actions. Drilling a new well to manage reservoir pressure can be the option of preference for one site, for a different site a new well may not be possible at all, or not within a viable timeframe. In this project, a series of reference storage sites, based on existing CO_2 storage studies resulting from other projects (e.g. EU projects), were used to derive site-specific information. While these illustrate the likely range of outcomes and results, they were used to derive more generic conclusions regarding different aspects of remediation and mitigation measures. The aim is to provide the information and knowledge that is necessary for operators to apply the results to their specific site.

Main objective. The main objective of MiReCOL was to produce a handbook of corrective measures for CO_2 leakage: a description of the remediation and mitigation measures studied in the project for leakage of CO_2, inside and out of the storage complex. The tool supports an operator in translating the results to his specific site and in assessing the value of a given technique in terms of a comprehensive risk analysis before and after deploying the technique. This requires a study of the impact of a given technique on a number of levels.

To reach this overall objective, MiReCOL had a number of additional objectives:

- **Describe the current state of the art of corrective measures**.
  This leads to a deeper understanding of the efficacy of various techniques in mitigating the impact of a threat or leakage, as well as to a complete description of techniques in terms of a range of performance indicators (see next section). This work will be organised around leakage scenarios: well-related leakage pathways; leakage along faults or fractures; migration over spill points; migration to and from secondary accumulations in the overburden; and, finally, surface release. A thorough understanding of the mechanisms controlling these scenarios is a crucial part of the assessment of each corrective measure.
- **Explore and describe new mitigation and remediation techniques**.
  The toolbox available to storage operators has been extended with a number of new sophisticated techniques, which were investigated and described along the same lines as used for existing techniques.
- **Test a number of the innovative techniques in the laboratory and in field experiments**
  - The project made use of several field trials, including back production of CO_2 and injecting sealants into a fault. The sites available in the project encompass K12-B (Netherlands), Ketzin (Germany) and Bečej (Serbia).
  - Testing of remediation methods will be carried out at a smaller scale in the laboratories of SINTEF, IFPEN and Imperial.
- **Provide the knowledge base for the definition of protocols and safety regulations**.
  The complete and in-depth descriptions of corrective measures is published in a handbook, as well as in an interactive web-based tool; both are to be used by storage

operators, for the definition of a corrective measures plan (prior to the start of injection) and for use when a threat or leakage has been detected and corrective measures are to be deployed. The knowledge produced in this project is also useful for competent authorities, to advance their understanding of the options available to mitigate or remediate unwanted events in a storage project.

1 MIRECOL: CORRECTIVE MEASURES FOR CO2 STORAGE PROJECTS

The EU FP7 MiReCOL project (2014-2017) investigated a wide range of potentially useful methods to correct, or mitigate the effects of, non-conformance, focusing on application in the deep subsurface, within or close to the storage formation. The point of view was that correction or mitigation close to the origin of the cause could be more effective than near the surface, where the CO_2 is likely to have become dispersed and difficult to detect.

1.1 Project set-up

The starting point for all MiReCOL studies was a storage complex (containing the storage formation, a sealing formation, at least one injection well and a quantity of CO_2 already injected) in which CO_2 behaves unexpectedly. This could be due to, for example, an open fault or an undetected spill point. Three classes of causes for the non-conformance were considered, each with a range of corrective measures.

1. Loss of conformance in the reservoir due to reservoir compartmentalisation / discontinuity (leading to unexpected increase of injection well pressure), spread of the CO_2 plume beyond the desired region (e.g. spread beyond the spill point). Corrective measures are mostly pressure based. Section 2 summarises the results obtained in the project.

2. Natural barrier breach, referring to migration of CO_2 or displaced brine through seals, faults or fractures. Section 3 provides an overview of potential corrective measures to prevent CO_2 from travelling along faults or through the cap rock.

3. Well-related non-conformance. Although the entire body of experience on well-related remediation from hydrocarbon production is applicable in principle to non-conformance in CO_2 wells, a number of CO_2 specific techniques were assessed in the MiReCOL project. Section 4 summarises the results.

These results were used to compare the impact and efficacy of the correctives measures studied and to develop a remediation portfolio optimisation approach. This is described in Section 5.

All results from the MiReCOL project are combined into a web-based tool. The tool is to provide guidance to operators and regulators about the applicability of the corrective measures assessed in the MiReCOL project. The tool can also be used as a handbook, as it provides access to all MiReCOL reports. Section 5.3 gives a brief overview of the tool and handbook.

2 LOSS OF CONFORMANCE IN THE RESERVOIR

Corrective measures that act within the reservoir can be characterized as operational migration management. Unexpected fluid flow within the reservoir can represent a threat to safe and secure storage, if e.g. the CO2 plume is migrating towards a spill point or a fault zone. Corrective measures considered include localized reduction in permeability by injecting gels or foams, by immobilizing the CO2 in solid reaction products, a change of injection strategy, or localized injection of brine creating a competitive fluid movement. CO2 migration management in the reservoir can also be achieved by either brine withdrawal or CO2 back-production. Both measures create pressure gradients towards the withdrawal point and enforce a specific flow direction. Data from back-production projects at K12-B and Ketzin were used to complement the model simulations.

Below, a few examples are given of potential corrective measures that could act within the reservoir. In all cases, the aim was to focus on the parameters that determine the effectiveness of the measure and to generate a database of results that can be used in the web-based corrective measures tool (see Section 5.3).

2.1 Flow diversion

The aim was to review and assess the efficiency of various mechanisms to modify CO_2 flow patterns in a storage reservoir. These include the use of gel, foam, brine injection, different injection strategies and the use of solid reaction products, all of which were tested by means of modelling and/or numerical simulation.

2.1.1 Brine/water injection as a flow diversion option

The aim was to test the effectiveness of brine injection for controlling unwanted migration of CO_2 within a reservoir.

Simulations were performed of CO_2 migration along a ridge structure in the Johansen aquifer offshore Norway (Figure 1), with water injection as a mitigation measure. Water is injected to try to prevent CO_2 from migrating further up the ridge. Twenty-one combinations of CO_2 injection rate, permeability and reservoir depth were simulated. The water injection period is one year, and simulation results are examined to determine the efficiency of the remediation measure to slow down migration and the longevity of the effect after water injection is stopped. While results varied little with depth, a higher permeability is correlated with smaller efficiency, probably due to relatively stronger dominance of gravity forces vs. viscous forces, and a smaller pressure gradient for a given water injection rate.

It was shown that water injection effectively stops CO_2 migration but does not provide a long-lasting effect, delaying CO_2 arrival at a point above the water injection point by only 1.4 to 7 years. Since migration of injected CO_2 will continue over many hundreds years, water injection cannot be considered a long-term solution.

Numerical simulations were set up to analyse an actual water injection test performed at the Ketzin CO_2 storage test site. Water injection for three months were performed in the period October 2015 to January 2016, with a total amount of 2884 tonnes of brine successfully injected. Mass flux, cumulative mass, density, temperature and electrical conductivity were continuously monitored (Figure 2). Pressure was monitored at 550 m downhole, and geo-electrical monitoring was performed.

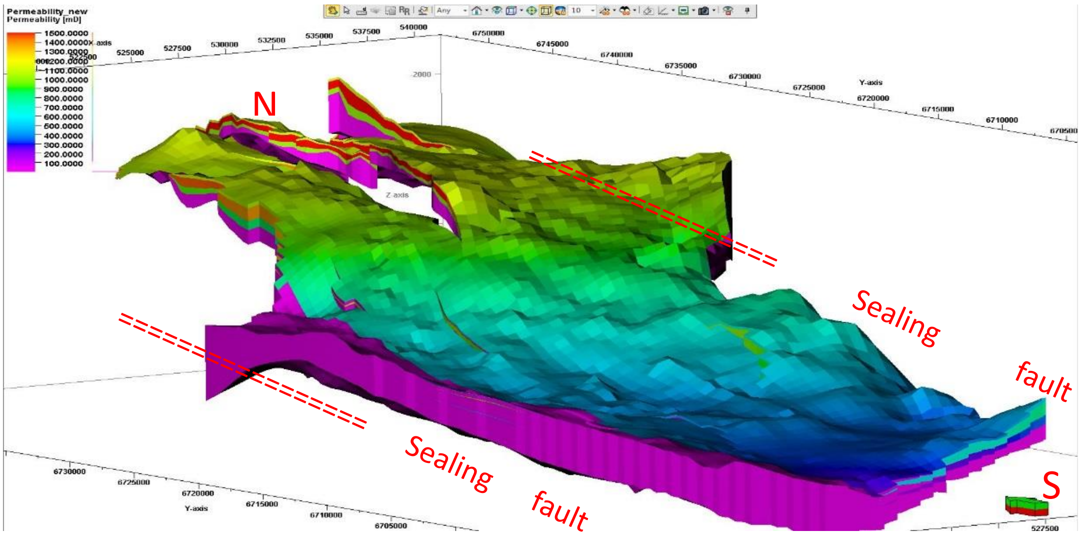


Figure 1: The Johansen model used in SINTEF's part of the study. A ridge-structure in the north-western part of this model was used to represent the undesired CO_2 migration path.

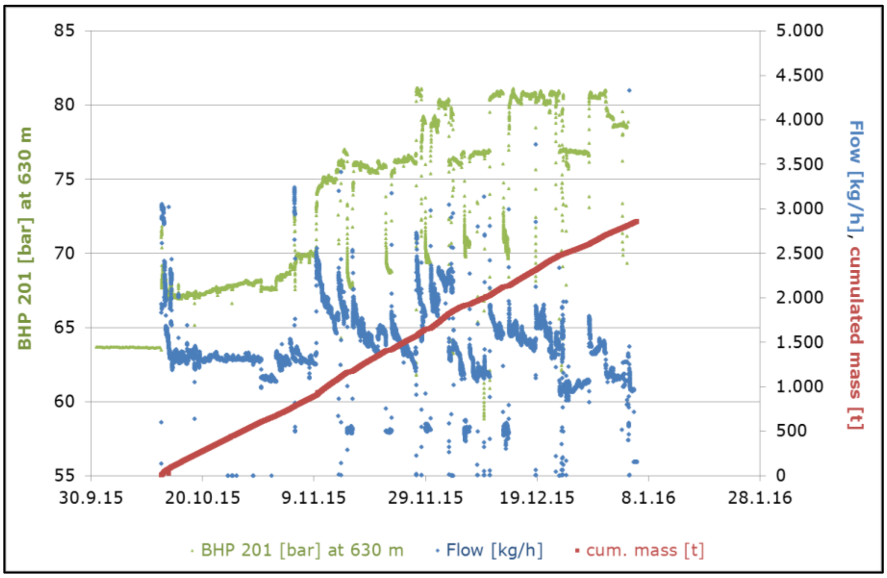


Figure 2: The main operational parameters (BHP, flow rate and mass injected) during the brine injection test period.

CO_2 re-enters the well after a period of a few months, confirming the observation that brine injection is a potentially fast-acting measure, but temporary and must be combined with more permanent measures.

The numerical simulation was performed on a model that had been calibrated to the CO_2 injection history. While the model match the bottom-hole pressure response during the previous CO_2 injection phase, it did not predict correctly the significant pressure increase and fluctuations during brine injection, even when hysteresis was included in the model. Some directions for further investigations to resolve the discrepancy are suggested, such as refining the grid discretisation in the vicinity of the well (presently with a 10 m grid). Another reason may be the presence of cemented fractures that affects the residual trapping efficiency.

Inversion of the geo-electrical monitoring data shows decreasing resistivities in the reservoir compared to the baseline and therefore shows the displacement of CO_2 by the injected brine.

2.2 Reservoir pressure management

During CO_2 injection into saline aquifers, increased reservoir pressure may lead to cap-rock failure or reactivate pre-existing faults, both having the potential to cause vertical leakage or unintended lateral fluid pathways leading to leakage beyond the spill point. To reduce the driving force for these types of leakage, pressure reduction and management in the reservoir is favoured as ultimate remediation measure. This pressure management may be achieved by back production of previously injected CO_2, withdrawal of brine/water from below or outside the CO_2 plume or by accelerating the CO_2 dissolution in the formation brine. These remediation measures are studied by numerical modelling on various reservoir models and are accompanied by laboratory work and a large scale CO_2 back production field test at the Ketzin pilot site, which supports the numerical simulation work by real data.

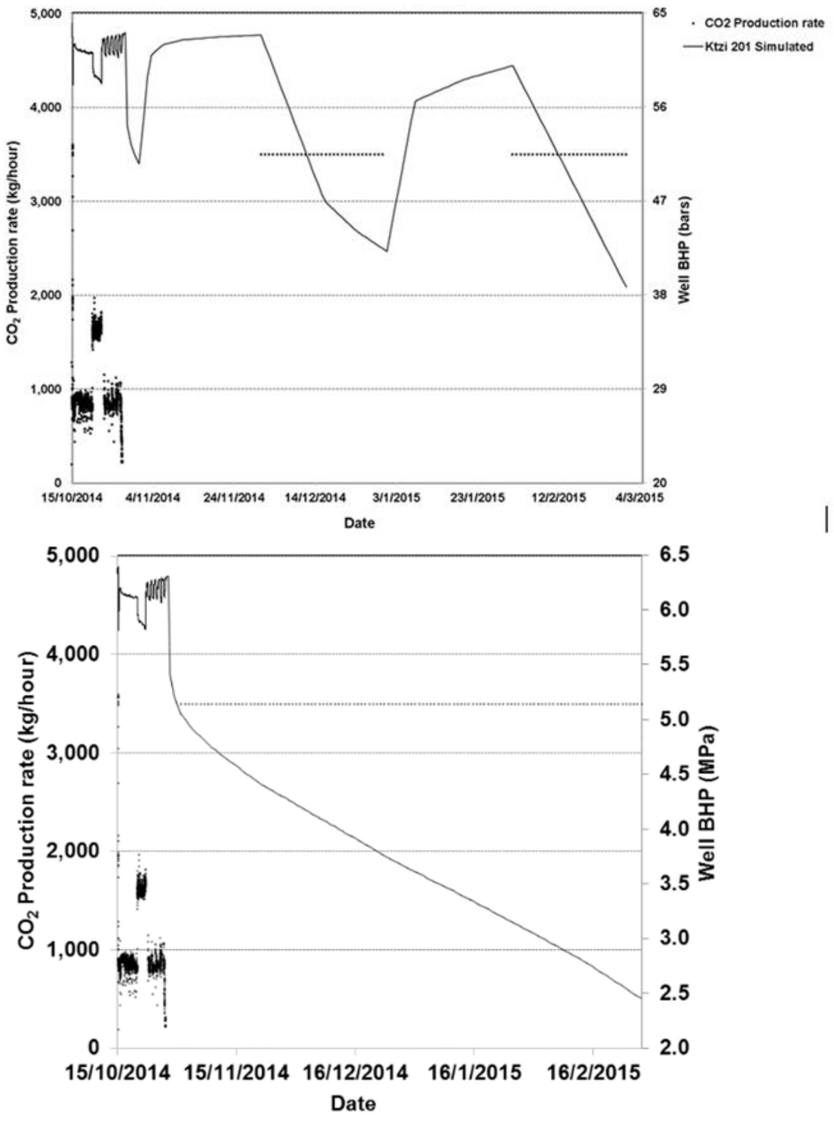


Figure 3: A (above): Simulated long-term well bottom-hole pressure (BHP) at Ktzi 201 for a scenario considering CO2 back-production at a constant rate. B (below): Simulated long-term bottom-hole pressure (BHP) at Ktzi 201 for a scenario considering CO2 back-production at a variable rate.

2.2.1 Performing and modelling CO_2 back-production field test campaign at Ketzin

After the completed operational phase of the Ketzin storage pilot, the history matching of the field trial was carried out for the bottom-hole pressure (BHP) of the wells Ktzi 201(injector) and Ktzi 203 (3rd observer). Two extended back-production scenarios (duration assumed until March 2015) were considered: (1) constant peak-rate of 3,500 kg/hr (Figure 3A), and (2) variable rate (on-off) of 0 – 3,500 kg/hr (Figure 3B). For both regimes, the results for the simulated bottom-hole pressures at Ktzi 201 indicate a clear pressure reduction in the range between 10-40 bars in these long-term back-production scenarios. Therefore, the applied mitigation measure can be confirmed as pressure management tool. But in the context of risk level estimation, corresponding geomechanical effects due to pressure relief have to be carefully observed and investigated.

3 NATURAL BARRIER BREACH

The feasibility of reducing or interrupting leakages through faults and fracture networks was considered by assessing the efficacy of reducing pressure to lower the leakage rate, or of using sealants (gels, foams) to close the leak. In addition, several other possibilities were explored, like transferring CO2 through a fault in a compartment originally unconnected to the main reservoir, improving the sealing capacity of a cap rock by injecting nitrogen before or during CO2 injection or generating a flow barrier above the cap rock by creating a reverse pressure gradient.

3.1 Transport properties of faults

The objectives of this element of MiReCOL were to investigate remediation options linked to transport properties of faults and fracture networks. Fractured caprocks and faults intersecting the caprock are of primary concern as they can act as conduits for CO_2 migration out of the storage reservoir.

3.1.1 Remediation of leakage by diversion of CO_2 to nearby reservoir compartments by fault reactivation

This potential corrective measure revolves around diverting CO_2 from the storage compartment to nearby reservoir compartments through fractures or a deviated well (Figure 4 and Figure 5). The mitigation method requires creating a pathway for fluid migration between the injected, leaky compartment and neighbouring compartments, as the injected and neighbouring compartments are originally not connected (Figure 5).

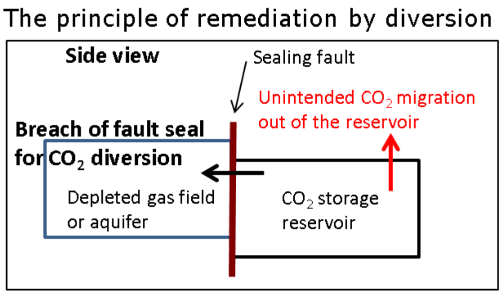


Figure 4. The principle of remediation by flow diversion from the CO2 storage reservoir to the adjacent unconnected reservoir. Hydraulic connection between the two reservoirs separated by a sealing fault could be achieved by drilling a deviated well or by creating hydraulic fractures through the fault seal.

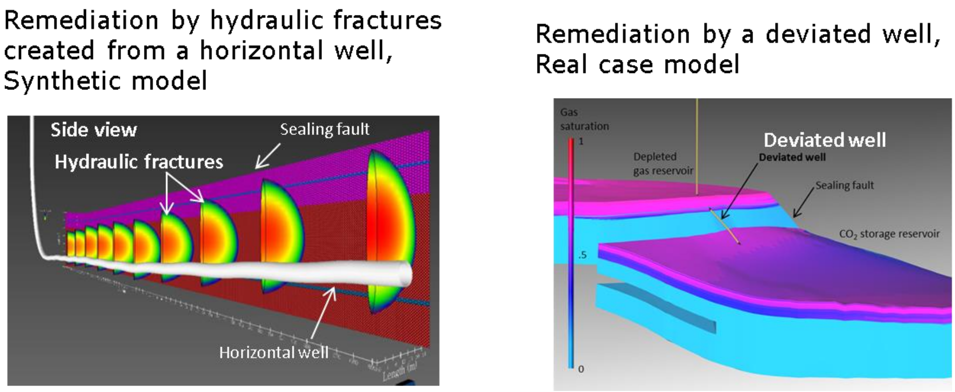


Figure 5. Breaching of fault seal by hydraulic fracturing (left) and drilling a deviated well (right) to enable lateral migration of fluids between the two adjacent reservoirs separated by a sealing fault.

Compartmentalized gas reservoirs or aquifers represent geological settings potentially suitable for remediation by flow diversion. Such structural settings are quite common in the Dutch and the North Sea reservoirs; for example, the depleted P18-4 gas reservoir, which holds a CO_2 storage license under the CCS Directive, is separated by a sealing fault from the neighbouring P15 depleted gas field (Figure 6). Another example relevant for CO_2 storage in both depleted gas fields and aquifers, are the Rotliegendes reservoir rocks, which are compartmentalized throughout the North-western Europe.

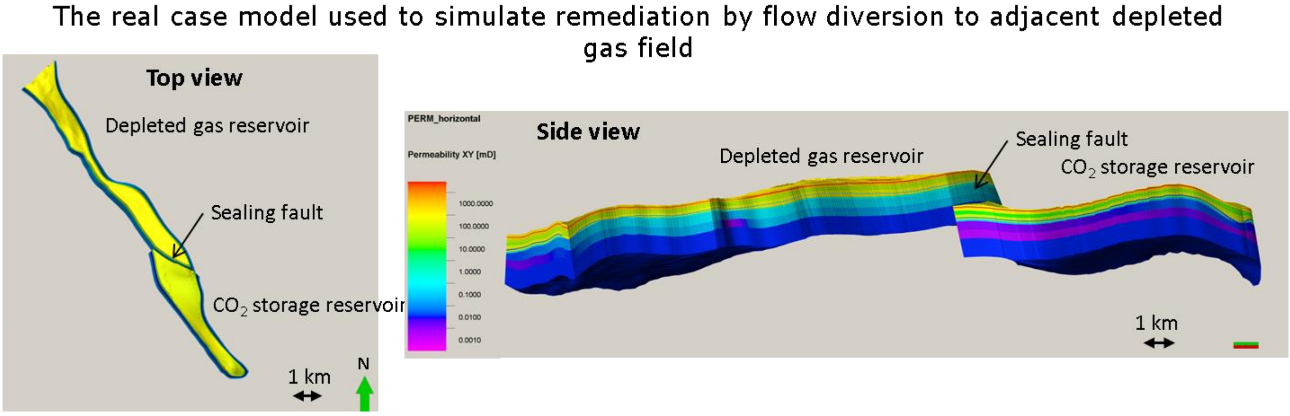


Figure 6. Top view (left) and side view (right) of the real case model used to simulate remediation by flow diversion from the CO2 storage reservoir to the adjacent depleted gas reservoir.

Our study demonstrates that in the event of significant irregularities and leakage from a CO_2 storage site, pressure relief can be achieved by diverting the CO_2 from the storage compartment to non-connected parts of the reservoir, or to adjacent reservoirs and aquifers. Fluid migration between the two originally non-connected reservoirs could be enabled by hydraulic fracturing across a sealing fault that separates adjacent compartments, or by drilling a well or laterals. The effects of flow diversion as a remediation option were evaluated through numerical simulations of idealized synthetic case and a real field case from the North Sea (Figure 6). The results show that flow diversion is a possible remediation option for a specific setup of depleted gas fields or saline aquifers, which is common in the Dutch and the North Sea portfolio of reservoirs. The key factors controlling the efficiency of flow diversion are: the conductivity of the created pathways between the two reservoirs, the pressure difference between the reservoirs and the permeability of the receiving reservoir. In the case of CO_2 diversion into an undepleted saline aquifer, the remediation is relatively slow, compared to diversion into an adjacent depleted gas field, due to the small pressure difference between the two compartments.

3.2 Fault sealants

The oil and natural gas industry uses a number of techniques to reduce the flow rate of a given fluid, or maximizing oil or gas recovery by injecting fluids with specific properties. The objective was to review, select or adapt some of these techniques for reducing or stopping the undesired migration of CO_2 through fractures.

The example given here concerns polymer-gel injection to divert flow within the reservoir. The objective was: i) to perform simulations of polymer-gel injection with different remediation layouts after CO_2 leakage has been detected, ii) to estimate the area of influence and the volume of polymer-gel solution required (and cost) for each remediation scenario. Leakage through a sub-seismic fault 1,000 metres from the CO_2 injection well was detected inside the shallow aquifer within a few months of injection, assuming 5,000 tonnes of mobile CO_2 as the lower limit for detection[1]. CO_2 injection was temporarily terminated until polymer-gel treatment in the reservoir is carried out. The remediation performance was subsequently assessed with a post remediation CO_2 injection to complete a total of 5 years simulation period.

A number of remediation scenarios were considered using horizontal well configurations as the polymer-gel injector (Figure 7). The scenarios were based on:

- polymer-gel viscosity.
- depth of polymer-gel injection in the reservoir.
- proximity of polymer-gel injection to the leaky sub-seismic fault.

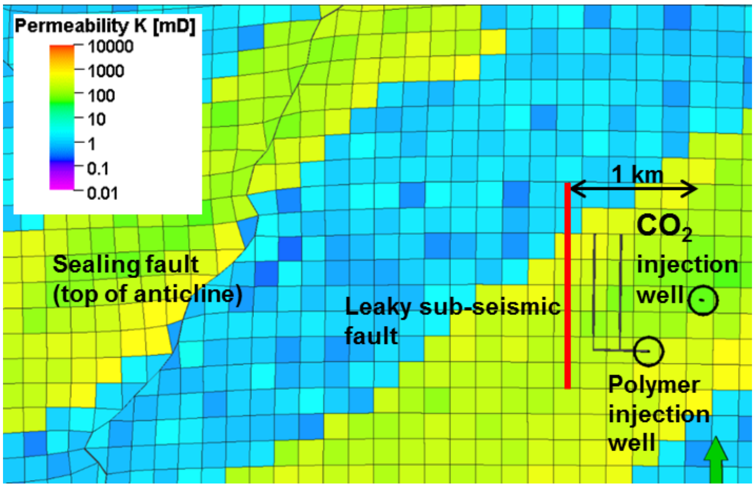


Figure 7: **Location of polymer injection well, sub-seismic fault and CO_2 injection well.**

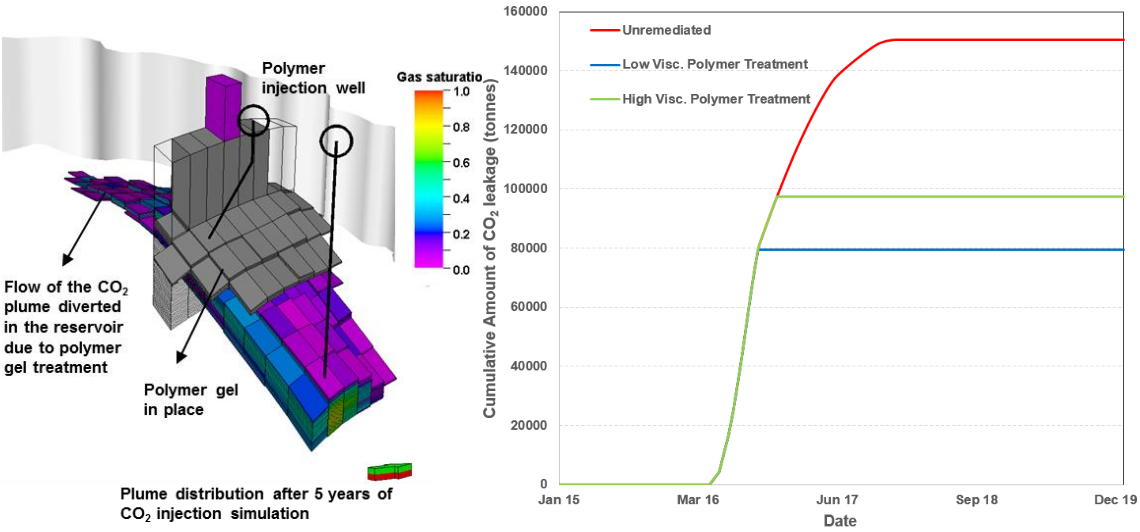
Polymer-gel injection well distances of 800, 400 and 200 m from the sub-seismic fault with high, medium and low viscosity polymer-gel solutions at the base and top of the storage reservoir were tested (Table 1). As an example, considering the low viscosity case 1 in Table 1, a very low

[1] Benson, S.M., 2006. Monitoring carbon dioxide sequestration in deep geological formations for inventory verification and carbon credits. Society of Petroleum Engineers, SPE 102833.

permeability zone illustrated by the grey region in Figure 8a was achieved after the polymer-gel treatment.

Table 1. Polymer-gel injection scenarios considered to assess its remediation performance for flow diversion in the storage reservoir.

Distance of polymer-gel injection from the fault (m)	Polymer-gel Viscosity	Scenario #	Amount of polymer-gel injected (Mt)	Length of injection period (days)
200	Low	1	0.29	30
	Intermediate	2	0.34	95
400	Low	3	0.59	60
	Intermediate	4	0.63	185



(a) (b)

Figure 8: The results of numerical simulations for Scenario 1 in Table 1 (a) CO2 plume distribution after 5 years of post-remediation CO2 injections, (b) performance comparison of remediation measures for cases of unremediated leakage, low and high viscosity polymer-gel treatments.

The results have shown that the polymer-gel solution seals the fault and diverts the CO2 flow as desired. In the scenarios considered, an appreciable reduction in CO2 leakage was thus achieved depending on the viscosity of the polymer-gel used and the distance and positioning of the horizontal well with respect to the laky fault, and no CO2 leakage was observed after the implementation of polymer-gel treatments.

3.3 Barriers

The work on barriers had two objectives: 1) test a mitigation technique to prevent CO_2 migration in the caprock using nitrogen injection; 2) test a hydraulic barrier method after CO_2 migration in the caprock using water injection.

Here an example is shown of the results concerning the N_2 barrier. Current CO_2 storage operations in aquifer reservoirs are naturally limited, among other parameters, by entry pressures encountered in cap-rocks, thus limiting over-pressures allowed during the storage process. The injection of nitrogen in a zone just below the cap-rock, prior CO_2 injection, could be a viable protective measure to increase the storage safety by lowering the leakage risk and increasing the maximum allowable reservoir pressure. The concept governing the injection of N_2 is summarized in Figure 9.

The physical background of the beneficial impact of Nitrogen on the caprock entry pressure is based on the higher N_2–brine interfacial tension (IFT) compared to CO_2–brine. As a maximum possible effect (for pure N_2-brine systems), IFT could increase by a factor of two, yielding correspondingly to the same increase of allowable pressure. However, the N_2 injection decreases the storage volume and the trade-off must be studied carefully. The IFT spread decreases rapidly with the mixing ratio of CO_2 in the N_2. Mixing can occur due to advective processes induced by differential absolute pressure due to CO_2 injection and also due to vertical mixing due to different partial pressure. Injection placement is studied carefully, especially the vertical conformance as well as saturation rarefaction.

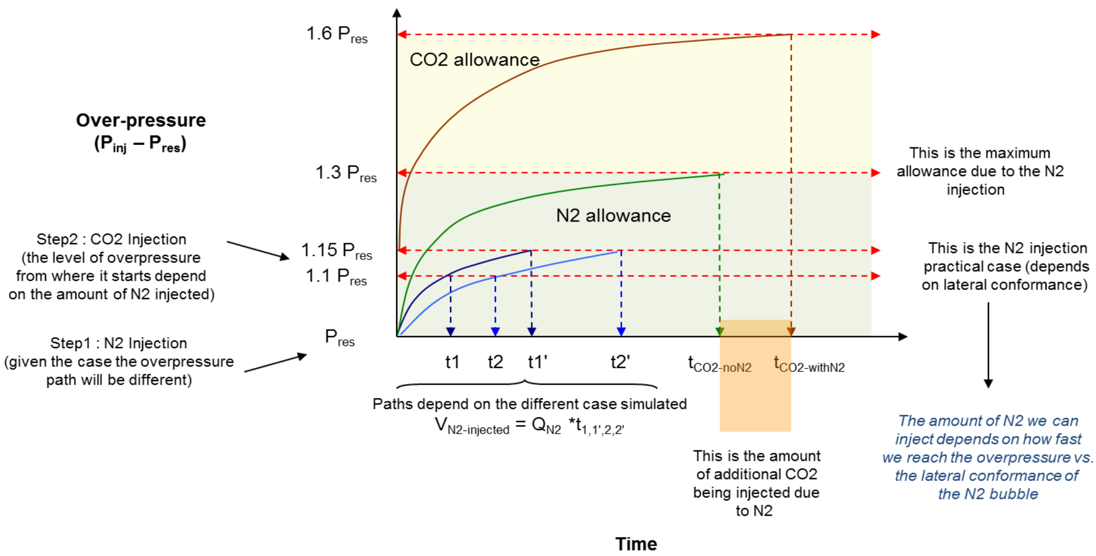


Figure 9: Conceptual design of an N_2 injection prior to a CO_2 injection.

In order to study the feasibility of such an approach for different storage conditions, a series of CO_2 injection simulations were performed within a generic characterization framework based on dimensionless numbers. A database of dimensionless numbers governing the storage was built, using literature information. The application of an experimental design based on the minimum/maximum values found within the data-base identified a series of cases to be simulated, further reduced by a fractional approach of such design. The scenarios simulated consisted of a CO_2 injection within a reservoir storage zone found at some distance from the N_2 zone, just below the cap-rock, followed by a resting period during which the CO_2 saturation is monitored. The N_2 zone is refined, rendering possible the study of the potential mixing and contamination with CO_2. For all case members of the data base, the CO_2 conformance was studied in terms of possible mixing and override of the CO_2 plume. Among all results (16 cases simulated) only 5 are recognized as being favorable for an N_2 injection as a preventive leaking measure, since no CO_2 reached the upper layer, neither at the end of the injection period, nor after the resting period of 10 years. The favorable cases were Case 6/7/14/15 and 16. These cases show the following dimensionless numbers (see Table 2 below). The definition of these dimension-less numbers can be found in deliverable D7.2.

Essentially, from the analysis of Table 2, heterogeneity (VDP number) does not play an important role in the CO_2 placement with regard to the cap-rock. All favorable cases have the same aspect ratio (low), the same capillary number, almost the same Sgr and the same buoyancy number, Ng (low). The role of the vertical movement due to low Ng and low vertical permeability Kz, which enters in the aspect ratio term is evident. Those two numbers drive the CO_2 setting, and therefore the capacity of the CO_2 to eventually contaminate the upper layer where the N_2 would be injected. The role of the mobility ratio is more ambiguous and plays a role when the gravity number is high (Case16).

Table 2. Dimensionless numbers for all favorable N_2 injection cases.

Case	Aspect Ratio	Dip	Mobility Ratio	Buoyancy Nb.	Capillary Nb.	Sgr	VDP
6	1.58	3.52	1.45	13.89	0.000301	0.38	0.6
7	1.58	3.52	54.61	13.89	0.000301	0.37	0.6
14	1.58	3.52	1.45	13.89	0.000301	0.38	0.8
15	1.58	3.52	54.61	13.89	0.000301	0.37	0.8
16	1.58	0.17	54.61	1562.1	0.000301	0.38	0.8

4 WELL-RELATED NON-CONFORMANCE

The oil and gas industry has a best-practice portfolio of remediation technologies in place, which is also applicable to CO_2 injection wells. New developments and emerging technologies were considered in the project. Laboratory tests were performed to examine the merits of CO_2-reactive suspensions, of polymer-based gels, of smart cements with a latex-based component and of polymer resins for squeezing. A field test was held at the Serbian Bečej natural CO_2 field, where the effectiveness of a CO_2-reactive suspension to seal the well was demonstrated.

4.1 O&G best practice

The general objectives of the work described below are to describe the most relevant well leakage scenarios and to review and assess the oil and gas industry best practice remediation measures in case of a CO_2 leakage event through a well.

The objective here was to evaluate existing and novel remediation technologies from the oil and gas industry and their application to CO_2 leakage from wells. A generic and systematic approach was used in the discussion of the most critical well barrier elements (WBEs). A large portion of the referred findings and discussions is based on personal field experiences by the authors and well integrity studies for the O&G industry and authorities. Different leakage scenarios for an operating CO_2 well with 14 WBEs have been mapped and discussed together with preventive actions based on field experience. Technology gaps for mitigation and remediation operations for leaking wells are given.

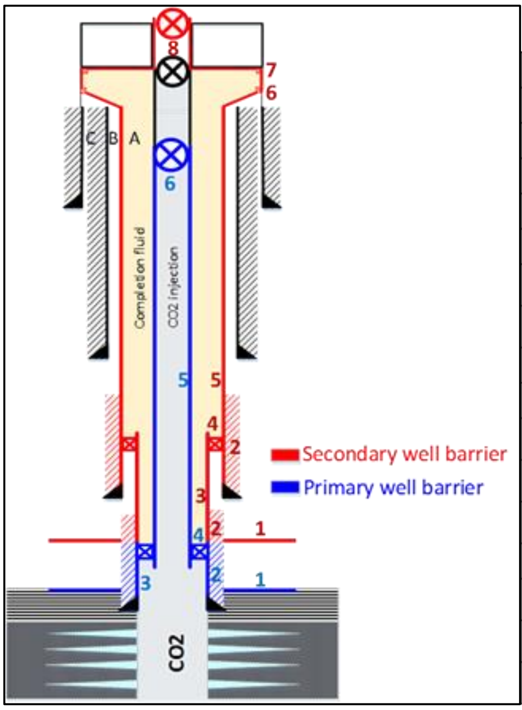
For simplicity, only one kind of well was considered and a typical CO_2 injection well was used to define WBEs, as shown in Figure 10 (see also report D8.1). The best analogue to this well in an O&G setting is an operating gas well with high CO_2 content and high gas-oil ratio. The fundamental well design for O&G and CO_2 wells are almost identical except for material selection, which is more critical for CO_2 wells.

A WBE is defined as a physical element to prevent flow and will in combination with other WBEs form a well barrier. The key WBEs are numbered and labelled as shown in Figure 10. The different WBEs in this case form two separate well barriers. A leak occurs when WBEs from both barriers fail at the same time. Early leak events are often related to:

- Improper well design;
- Wrong material selection;
- Improper installation of WBEs;
- Operational envelope outside the well design envelope; or
- Insufficient or now effective testing methodology

Reasons for late leaks are often related to:

- Corrosion or erosion;
- Fatigue and degradation of materials; or
- Loads on WBEs outside initial design due to change of well application (e.g. converting a producer to an injector).



No.	Well barrier component
PRIMARY WELL BARRIER	
1	In-situ formation (impermeable and moveable)
2	Liner cement (below production packer)
3	Liner tubular (below production packer)
4	Production packer
5	Completion string (tubing, components)
6	Downhole safety valve (including control line)
SECONDARY WELL BARRIER	
1	In-situ formation (impermeable and moveable)
2	Casing cement (above production packer)
3	Production liner (above production packer)
4	Production liner packer
5	Production casing
6	Casing hanger seal
7	Tubing hanger seal (neck seal)
8	Wellhead / surface tree

Figure 10: Well barrier elements for a typical CO_2 injection well.

WBE failures/defects were linked with common mitigation and remediation practices, including some new ideas. An assessment is given of the probability of WBE failure and of the consequences of a leak in terms of cost impact, time and schedule impact, and health safety and environment.

Experience from the O&G industry has shown that mitigation and remediation actions can be complex and costly. The report therefore also discusses some preventive actions to be taken in the planning phase for WBEs, that should reduce the risk of failures.

Finally, the report discusses technology gaps for more robust CO_2 well design. Some of the most important are:

- Improved well testing procedures and criteria during the construction and well barrier installation phase to be more suitable for gas/CO_2 wells;
- Re-installing of annular cement and barrier verification through multiple casing strings;
- Through-tubing cement bond logging for external casing cement;
- Alternative sealing materials to conventional cement with improved long term properties;
- Continuous monitoring of well integrity of in-situ formations and liner cement.

4.2 Novel materials

The aim was to review and assess the efficiency of new developments and emerging technologies for mitigation and remediation of leaking CO_2 wells, to perform laboratory tests for validation of selected novel materials and to describe current knowledge gaps.

4.2.1 CO_2 reactive suspensions

A method was studied for reducing the permeability in the near-well region using a reactive suspension. Among the many possibilities and after careful consideration of the literature, a process involving the precipitation of silicate from silica-alkaline solutions was selected. The initial pH of such solutions is about 12 (tuneable) and amorphous silica is formed when the pH is lowered to about 9. Once precipitated, back-dissolution by natural mechanisms is very unlikely and hence long-term stability is expected. Ideally, the injected solution should react with any CO_2 present in the formation and form amorphous silica, that will greatly reduce the permeability. The effect will depend on the amount of CO_2 present. To investigate the full permeability-reducing potential of the method the study included reaction with a (stronger) acid in addition to reactions with CO_2. The study comprised laboratory tests using generic samples (sand-packs, sandstones, carbonates) representative of geologic formations suitable for CO_2 storage, but also specific samples from the Becej field in collaboration with NIS (Naftna Industrija Srbije, Serbia). Bulk studies have also been performed to investigate gelation time and viscosity changes. A field test has been conducted to test the efficiency of the reactive suspension method.

Initial tests in porous media at 10 bar showed a water permeability reduction of a factor of 6 after flooding a rock sample saturated with the reactive suspension. Further tests with a different reactive suspension composition, and at 50 bar, showed a complete blocking of the rock sample after 10 min CO_2 flooding. This demonstrated a challenge in trying to control the precise reaction time of the solution. Controlled test of the gelation time were conducted by measuring the development of the viscosity of carefully prepared mixtures of the reactive suspension with acetic acid. The potential full strength of the silica precipitated in rock was also tested by letting this mixture cure for 24 h and then measure the differential pressure needed to allow brine to flow through the rock. In one example 20 bar was necessary to give a significant flow rate through a 3 cm rock sample, giving a gel strength of the order of 600 bar/m (Figure 11).

4.2.2 Field test of CO_2-reactive suspensions

The material described in the previous section has been tested in a a field test at the Becej site. A well was identified at the Becej site where the near-well region contains free CO_2 and where it would be possible to conduct the field test.

Final laboratory tests of the reactive suspension were conducted with rock samples from the Becej field in order to tune the suspension mixture to fit the downhole conditions. The field test was executed during August 2016.

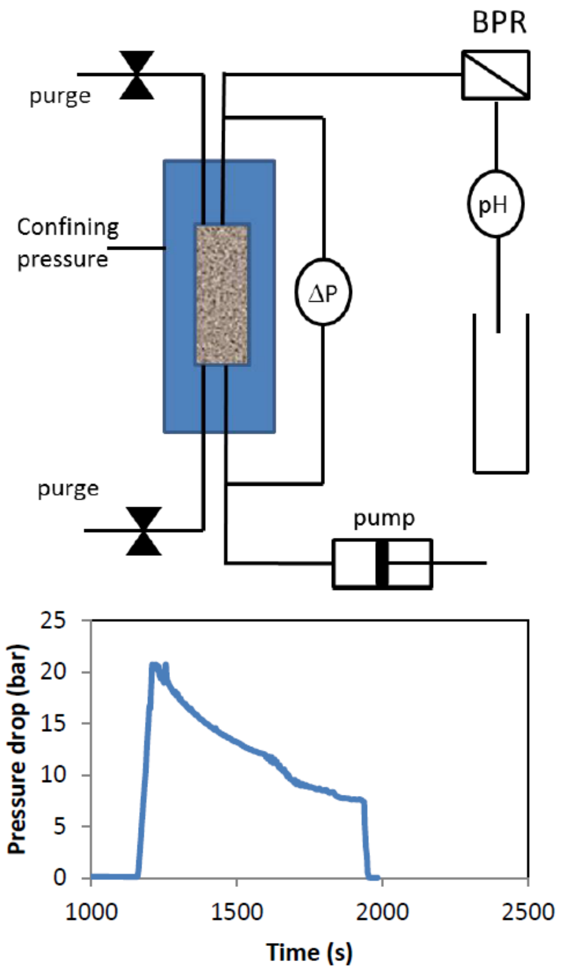


Figure 11. Simplified schematic of the experimental set-up for testing strength of reactive solution in porous media. As shown in the lower panel, a differential pressure of 20 bar was needed to displace brine through the sample, which in this case was 3 cm long.

4.2.3 Polymer-based gels for remediation of well leakage

The main objective was to investigate the sealing properties of polymer-gel solutions at the rock-cement-casing interfaces as well as induced fractures through cement under simulated down-hole conditions. A series of laboratory tests has been conducted, using the wellbore cell of Imperial College (Figure 12).

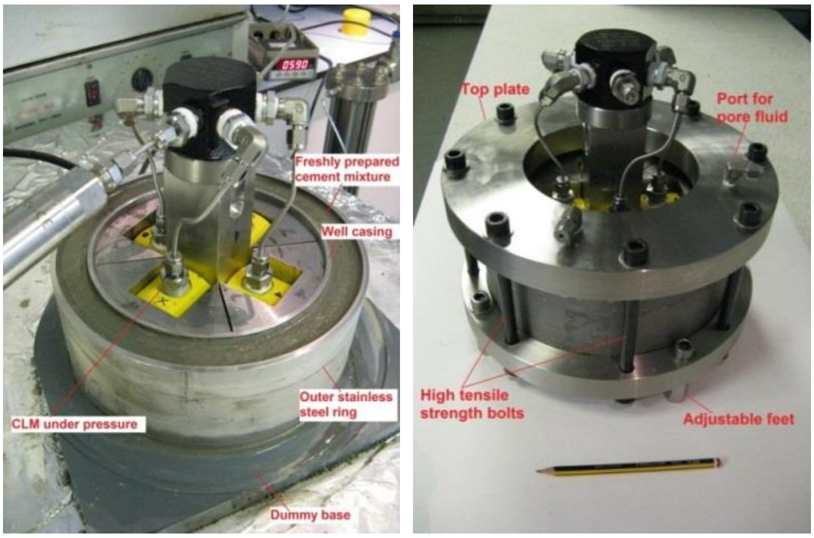


Figure 12: The wellbore cell of Imperial College. A central loading mechanism is used to generate varying mechanical load on the inner cylinder and induce fractures after cement curing.

A high molecular weight polyacrylamide-based polymer compound, crosslinked by a water-based zirconium chelate crosslinker, was used in laboratory tests performed at deep North-Sea conditions (92 °C, ~35 MPa). Polymer and cross-linker concentrations were tuned for gelation time and strength. N_2-permeability in generated fractures were measured before and after polymer-gel treatment (Figure 13), showing a reduction of about 80–90 %.

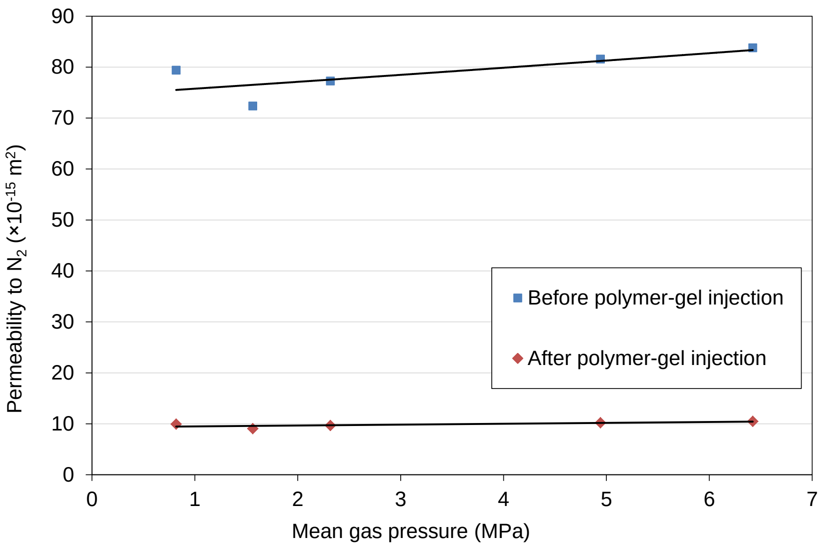


Figure 13: Changes in wellbore cement fracture permeability to N2, with mean gas pressure, before and after polymer-gel treatment.

Numerical modelling was performed to evaluate the efficiency of polymer-gel near-well treatment for reducing well-related CO_2 leakage on a field scale. For this, a generic model (ISCAM model) was used to represent a deep CO_2 storage site where the injection well starts leaking immediately after the end of the injection period. The polymer-gel treatment was modelled as occurring 1 year after a detectable amount of CO_2 had migrated along the well to a shallower formation. Further development of CO_2 leakage was modelled for varying effective permeability reduction (Figure 14), indicating that permeability reduction should be at least 90 % for polymer-gel treatment to be an efficient remediation option. Alternative depths for polymer-gel injection was also investigated.

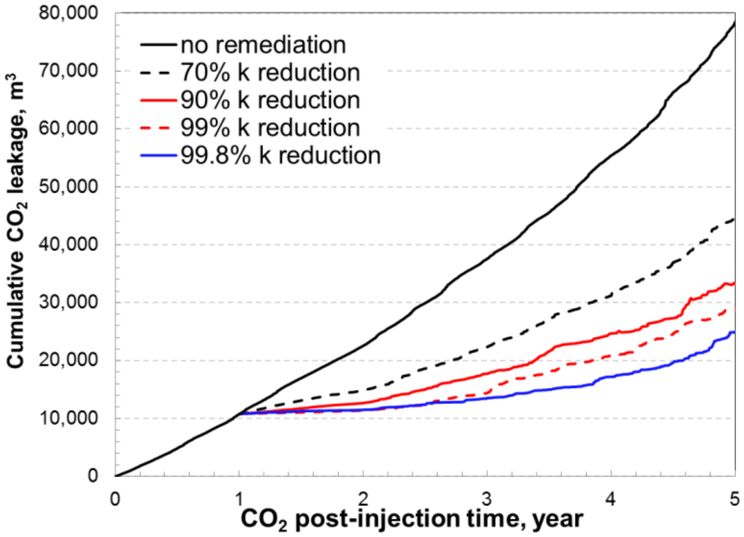


Figure 14: Simulated leakage profiles with and without polymer-gel treatment, and for varying effective fracture permeability reduction.

4.2.4 Overview of current knowledge and technology gaps for novel remediation technologies

The objective was to give an overview of current knowledge and technology gaps as a basis for further development of novel remediation technologies. The focus has been on the active phase of CO_2 wells (including intervention and workover phases), but subjects related to the drilling and abandonment phases are also discussed briefly. Data is always crucial to build a knowledge-based approach for identifying gaps for corrective measures of a problem. Since data from leaking CO_2 wells is still very limited, the major source of information has been the well integrity experience from the oil and gas industry, with expert judgement of additional CO_2-specific impacts (such as the corrosive nature of brine-CO_2 mixtures). The experience gained from laboratory and field tests, such as the Becej field test reported on in D9.2, will be essential to reduce gaps that are unknown to the CO_2 society.

Important issues being focused for oil and gas well plugging and abandonment, that also are relevant for CO_2 well integrity are:

- Well integrity in a long life (eternal) perspective;
- Well diagnostics to investigate multiple well tubulars;
- Special challenges related to annular cement quality and re-installation;
- Qualification of new materials as an alternative to cement;
- Testing and verification of new and re-installed well barriers.

Figure 15 illustrates a part of a well infrastructure including basic well barrier elements for a typical CO_2 well in operation. Current knowledge gaps are shown in green boxes on the left with connected issues in the black boxes.

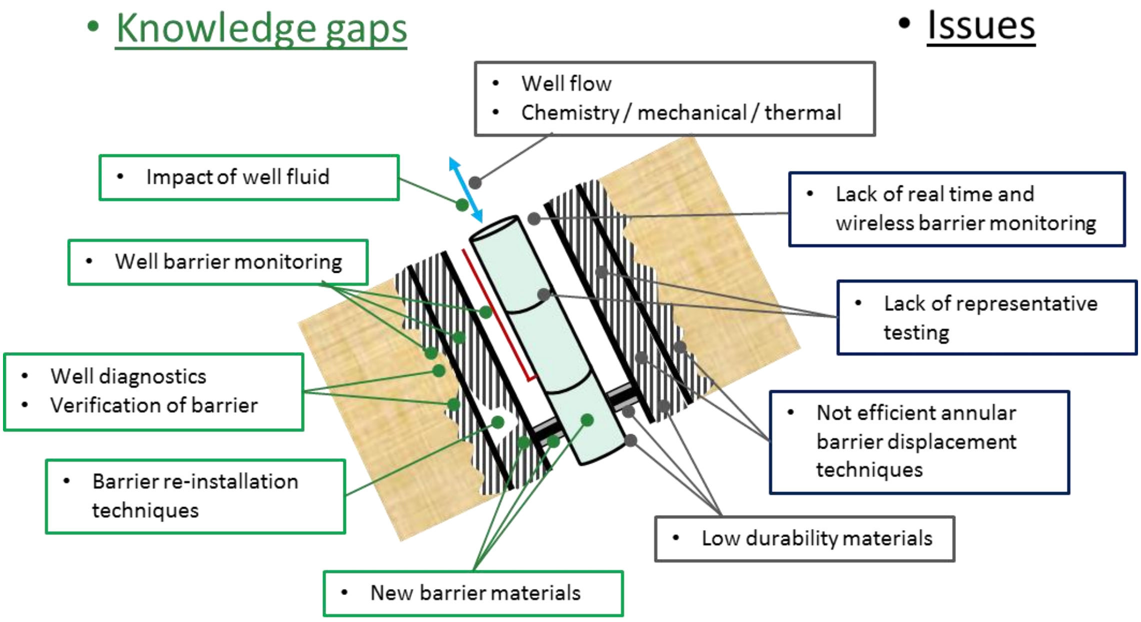


Figure 15: Schematics of an operating CO2 well showing knowledge gaps and issues.

The report D9.7 lists important technology categories for treatment of well leakages and gives an overview of the technology readiness level of novel technologies and methods that could close these knowledge and technology gaps. Worldwide sharing of CO_2 well data could be useful to develop a better understanding of the knowledge gaps, and implement best practices and trends for remediation techniques and methodologies for leaking wells. The R&D focus of the future should be on establishing a CO_2 well database consisting of both research experience and real field cases.

5 IMPACT AND EFFECTIVENESS OF CORRECTIVE MEASURES

5.1 Near-surface remediation

While strenuous efforts will be made to minimise the risk of the leakage of CO_2 from engineered storage sites, there will always remain a residual risk that CO_2 could migrate from the storage site into the shallow subsurface along permeable pathways such as faults or wells.

The objectives were to provide a comprehensive review of the available techniques for CO_2 leakage remediation in the near surface environment considering relevant experience and expertise from pilot scale CCS projects and natural analogues, CO_2-EOR operations, natural gas storage, and other industries as well as consider the cost and effectiveness of the techniques. The results from this work are documented in deliverable D10.1 which discusses the applicability of each available method to remediate CO_2 leakage in the near surface environment, the ease of implementation of the method and the associated costs.

The current industry best practises for the monitoring of CO_2 leakage in the near surface and the reporting required to aid the design of a risk-based remediation and reporting protocol provide a starting point in evaluating the relevance of near surface remediation techniques. The assessment that follows in the case of an incident involves an iterative process where the site characterisation / baseline data and the ongoing monitoring data feed into the risk assessment, which in turn informs the remediation action, and prompts further tailored monitoring and risk analysis.

A summary assessment was made of the probable role each of the different techniques with regards to CO_2 remediation. This assessment indicates that there is a wide range of remediation techniques available for near surface CO_2 remediation and that any remediation strategy will be site specific.

5.2 Impact and efficacy of corrective measures

The scoring/ranking of individual remediation techniques was implemented using an ordinal classification (low, medium and high) in five dimensions, namely: (a) likelihood of success; (b) spatial extent; (c) longevity; (d) response speed; and (e) cost efficiency, based on the results that were obtained for different scenarios (Table 3).

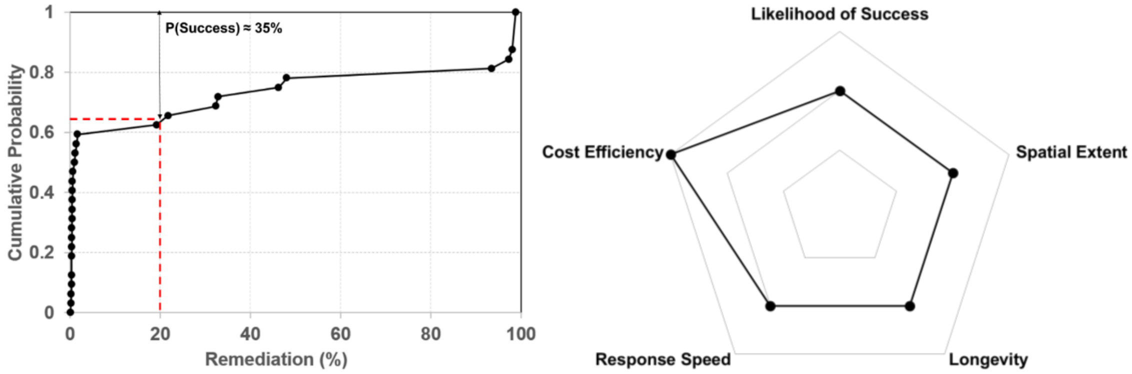
Table 3. Performance classification of leakage remediation techniques based on different criteria.

Rank	Likelihood of Success (%)	Spatial Extent (km^2)	Longevity (years)	Response Speed (years)	Cost Efficiency (M€)
Low	0 - 33	0 - 1	0 - 1	>1	> 10
Medium	34 - 66	1 - 5	1 - 10	0.1 - 1	1 - 10
High	67 - 100	> 5	>10	0 - 0.1	0 - 1

The spider chart outputs prepared were then used to standardise the performance scales in different dimensions in order to ensure that this is indicative of the overall merit of a given technique, and also allowing for a comparison between the leakage remediation techniques. The success probability charts and spider diagrams prepared from each modelled scenario for a remediation technique are shown below for one example.

Brine/water injection for CO_2 plume diversion within the reservoir

Several leakage mitigation scenarios were considered in MiReCOL by brine/water injection; Section 2.1.1 shows examples. Figure 16a illustrates that, if the desirable remediation level is assumed to be 20% or greater, the estimated probability of success for leakage remediation is 35%. A summary of the outcomes of the technique considering all the dimensions is illustrated in Figure 16b.



(a) (b)

Figure 16: Brine/water injection technique: (a) success probability; (b) spider chart

5.3 Remediation portfolio

The bow-tie analysis was used to facilitate the assessment of broadly two groups of techniques that were investigated in MiReCOL:

- threat barriers, referred to as risk mitigation techniques, for recovery and preparedness; and
- consequence barriers, referred to as remediation techniques, to reduce the severity of the consequences.

In order to develop a remediation portfolio optimisation approach, a methodology was developed based on the concept of decision trees, which are probabilistic models for structured decision making comprising of a sequence of one or more decisions and their respective possible outcomes, characterised by probability distributions, with the aim of maximising/minimising the expected value of a user-defined utility/cost function[2]. The rankings discussed as success probability plots and spider chart visualisations (see Section 5.2) under Task 11.1 were utilised and interpreted as a qualitative ranking system as presented in Table 4.

Table 4. Qualitative ranking of remediation techniques.

Label	Technique	Performance Characterisation Metrics				
		Likelihood of Success	Spatial Extent	Longevity	Response Speed	Cost Effectiveness
1	Foam injection	L	L	M	H	M
2	Polymer-based gel injection	H	M	L	H	L
3	Brine/water injection	M	M	M	M	H
4	Brine/water withdrawal	H	H	H	L	M
5	Solid reaction products	H	L	H	H	M
6	CO_2 back production	H	H	M	L	M
7	Hydraulic barrier	H	L	M	M	H
8	Polymer-based sealant for well leakage	H	L	L	H	H
9	Polymer-based sealant for caprock leakage	H	L	L	H	H

Remediation portfolio design and development

The design of the remediation portfolio was carried out in-line with the principles of modelling and evaluation of decision trees. Three types of nodes were initially identified to model the portfolio, *viz.* (a) the decision node (D), representing a point in time when the CO_2 storage site operator is obliged to make a choice from a given set of remediation techniques on the basis of his/her preferences (weights) for the performance metrics; (b) the chance node (S), associated with a random outcome which is anticipated by the operator as being either ‘success’ or ‘failure’ of implementation; and (c) the leaf node/endpoint (C), which represents a point where the cost function for an outcome of the terminal decision taken is indicated. Figure 17 illustrates the basic structure of the decision tree

[2] Fraser, N.M. and Jewkes, E.M., 2012. Engineering Economics: Financial Decision Making for Engineers. Pearson Education Canada.

developed for remediation portfolio optimisation. Numbers 1 to 9 in the figure represent the remediation technique label from Table 4.

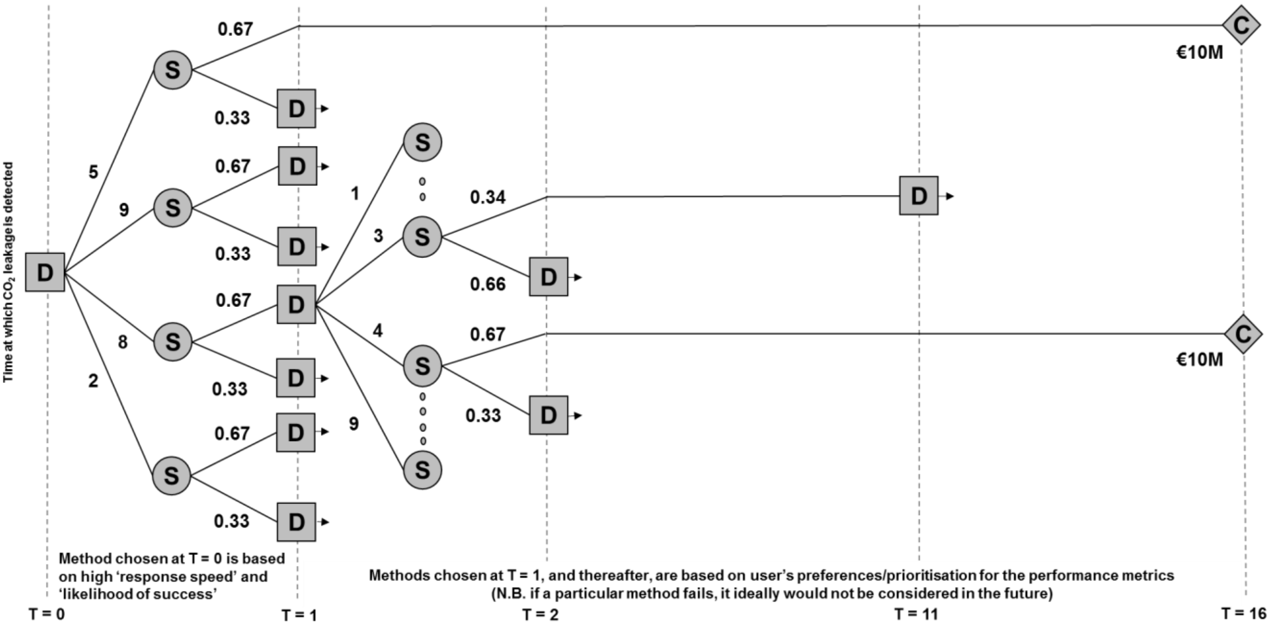
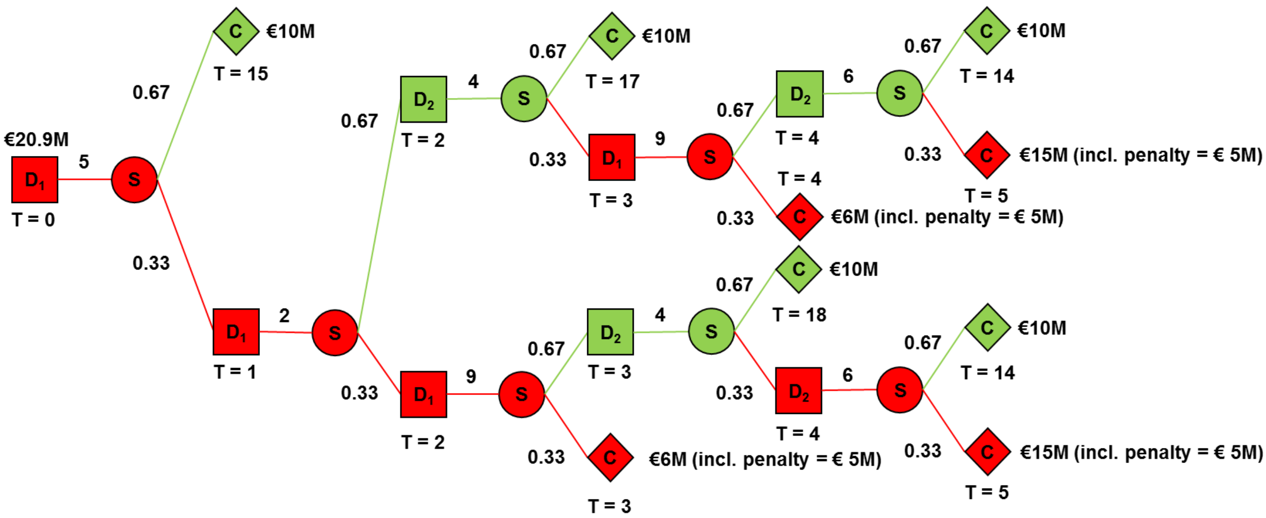


Figure 17: The decision tree structure for remediation portfolio optimisation.

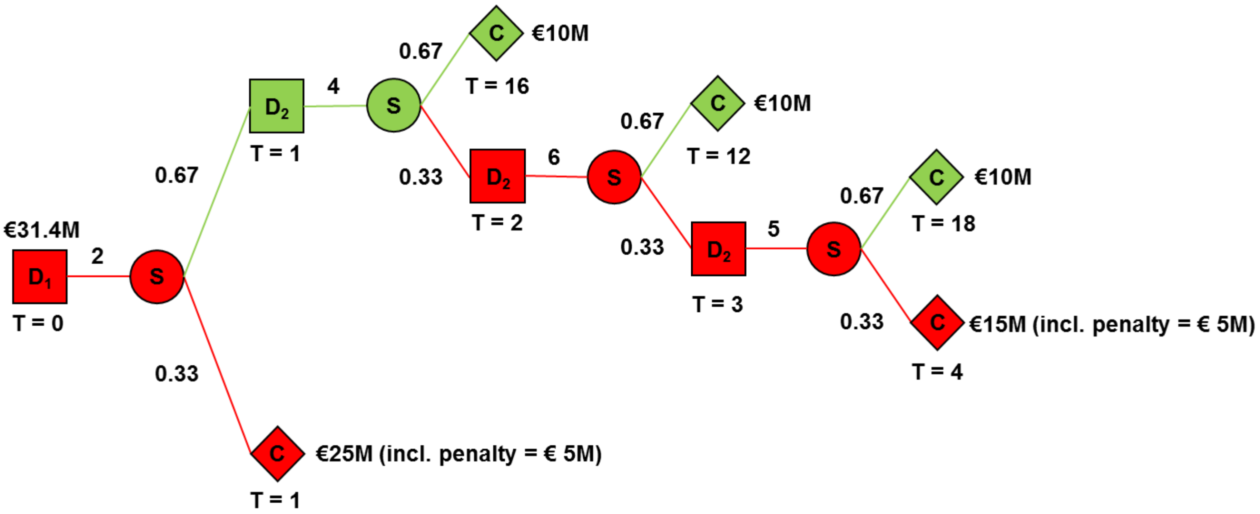
The timeline for decision-making begins when leakage is detected. The length of an individual decision time-step depends on the operator's choice, *i.e.* if the selected technique is successful, its longevity would define the length of the time-step. The methodology for remediation portfolio optimisation broadly comprises two steps, *Enumeration* and *Backward Induction*.

Two distinct scenarios were analysed to reflect the different operational constraints that apply to remediation options when leakage is detected (a) during the injection period, or (b) during the post-CO_2 injection period. Figure 18 and Figure 19 present examples of decision tree enumerations for each of these scenarios respectively.



Decision D_1 weights vector: [0.5, 0, 0, 0.5, 0]; Decision D_2 weights vector: [0.33, 0.33, 0.33, 0, 0]

Figure 18: Another example of decision tree enumeration for the remediation of leakage detected during the injection period.



Decision D_1 weights vector: [0.33, 0.33, 0, 0.33, 0]; Decision D_2 weights vector: [0.33, 0.33, 0.33, 0, 0]

Figure 19: An example of decision tree enumeration for the remediation of leakage detected during the post-injection period.

6 MIRECOL WEB-BASED HANDBOOK AND TOOL

6.1.1 Delivering the results: supporting the CO_2 storage site operator

For the results from MiReCOL to be operationally useful, the overall results should be presented in a ready-to-use way. Remediation technologies considered in this project were described 1) in terms of leakage prevention (technical efficiency), 2) impact on the overall risk level of a storage project, and 3) impact on the environment and cost-effectiveness. To this end, a number of key performance indicators (KPIs) were defined for each corrective measure: timescale to effective cessation of leakage, longevity of remediation, likelihood of success, economic cost, environmental impact at the surface, location of retention of the CO_2 (i.e. within reservoir, within storage complex etc.).

To improve the applicability of the project results and help clarify options open to site operators, a web-based tool was developed that evaluates these KPIs for each corrective measure, for a non-conformance case defined by the user. This provides insight in the applicability or relevance of corrective measures for the user-defined cases. In this way, the tool supports site operators to create a corrective measures plan for their site, and supports competent authorities to understand the options that are open to site operators in case of non-conformance.

The results from the MiReCOL project support the development of corrective measures plans and help build confidence in the safety of deep subsurface CO_2 storage by providing a toolbox of techniques to mitigate and/or remediate undesired migration of CO_2. The MiReCOL reports, as well as the corrective measures web tool, can be accessed through www.mirecol-co2.eu.

6.1.2 MiReCOL handbook

The MiReCOL online handbook groups together the remediation techniques, deliverables, and other literature from the project. This is organized in three tabs:

- Remediation techniques
- MiReCOL reports
- Downloadable literature

The default screen shows this tab. In the column to the left, you can see the different remediation techniques that were investigated in MiReCOL listed. Upon clicking one of the techniques, the page displays a brief overview of the technique, the methodology of either the remediation technique or the modelling of the technique, the materials related to implementing the technique, associated risks and impacts, application areas, case studies of this technique, the MiReCOL reports that deal with the technique, and references to information about the technique.

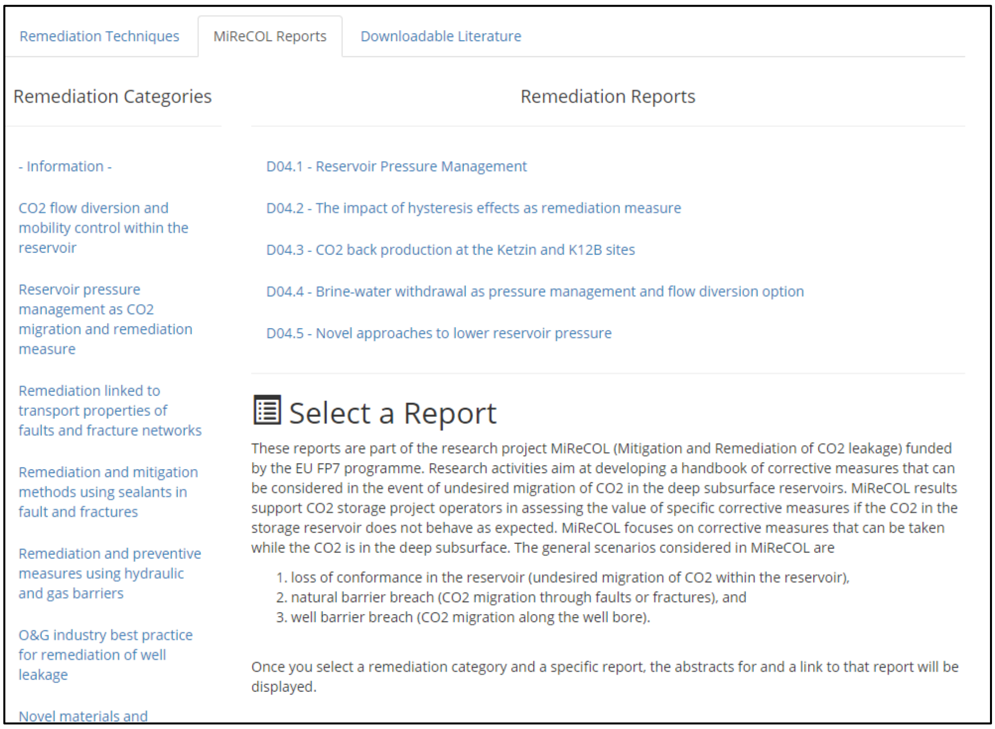


Figure 20. Screenshot of the MiReCOL reports structure on the online handbook that is part of the MiReCOL web app.

Clicking on the second tab takes you to the “MiReCOL reports” section of the handbook (Figure 20). In the column on the left, you see the list of remediation categories, which split up the remediation techniques into groups. By clicking on one of these, you will see a list of MiReCOL reports at the top of the main content area. Then, you select one of those deliverables, which will then display the abstract of the report, as well as a link to download the deliverable.

The final tab of the online handbook (Figure 21) is a large listing of the different literature that has come out of the MiReCOL project. This information is grouped into three categories: scientific publications, conference presentations, and MiReCOL deliverables. In the scientific publications are articles written during the project, while conference presentations contain the slides from MiReCOL presentations. Below those two sections, you will find a listing of the MiReCOL deliverables. You can select each listed item to download the piece of literature.

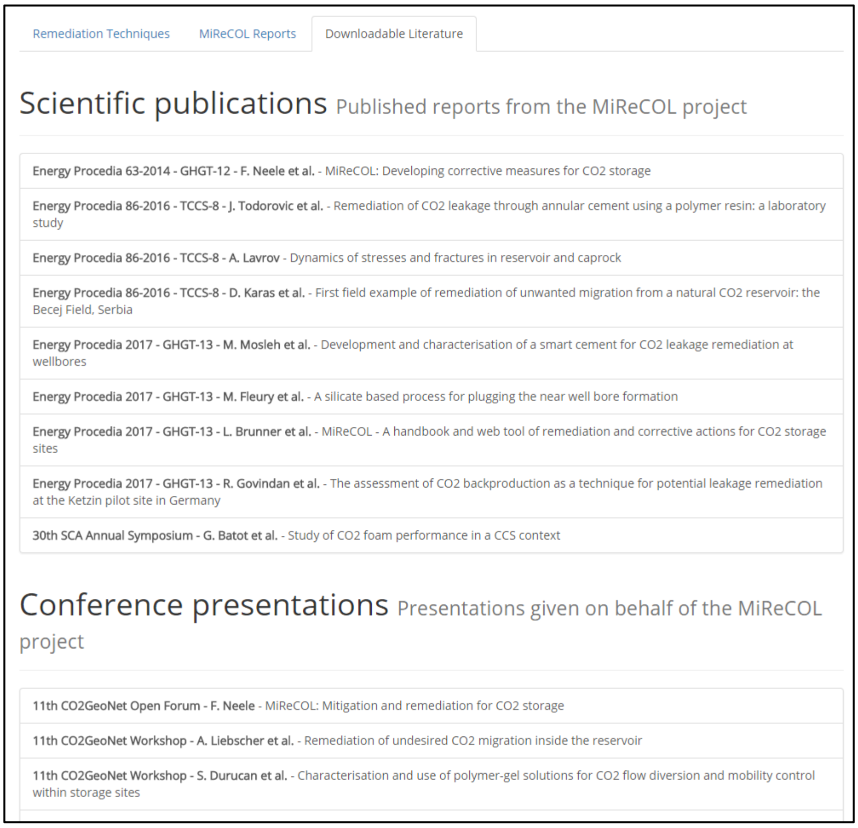


Figure 21. Screenshot of the downloadable literature page on the online handbook.

The physical copy of the handbook will be similar to the "MiReCOL reports" tab online, as described above, since the deliverables will be organized into this single document.

6.1.3 MiReCOL web-based tool

The main accomplishment of work package 13 is the development of the entire MiReCOL web-based tool (Figure 22).

The web tool allows the investigation of two types of remediation: "Site Remediation" and "Well Remediation". The former offers two functions:

1. Compare the leakage reduction potential from all the investigated remediation techniques based on their overall performance (Analyse all techniques).
2. Enter your site details, and find the closest scientific simulations for each remediation technique to determine their effectiveness (Site analysis).

The part of the tool that deals with analysing all techniques displays the results that are described above. This gives a broad overview of the overall method, as opposed to a scenario-based approach. The material here depends on the individual reports, as opposed to extra scientific simulations, as was done for the "site analysis" part of the site remediation tool. What is displayed for the all techniques analysis, is a brief overview of the technique, an interactive plot of the success of the technique (when considered in the context of the simulations performed), and a spider diagram that sheds light on the likelihood of success, spatial extent, materials/cost, response time, and longevity of the remediation technique.

The site analysis page was developed to use user input to define a site, then use the web tool to find the closest scientific simulations to that user's site, and then display the results from the scientists for that specific scenario. An example of the input is shown in Figure 23 and an example of the output is shown in Figure 24. To find the closest scenario between the user's input and the scientific simulations, the Gower Similarity Coefficient is used. It has been important to note that this tool does not use the actual user's input to find the output, but rather the closest scientific simulations done within the MiReCOL project.

Figure 22. Opening page of the MiReCOL web tool

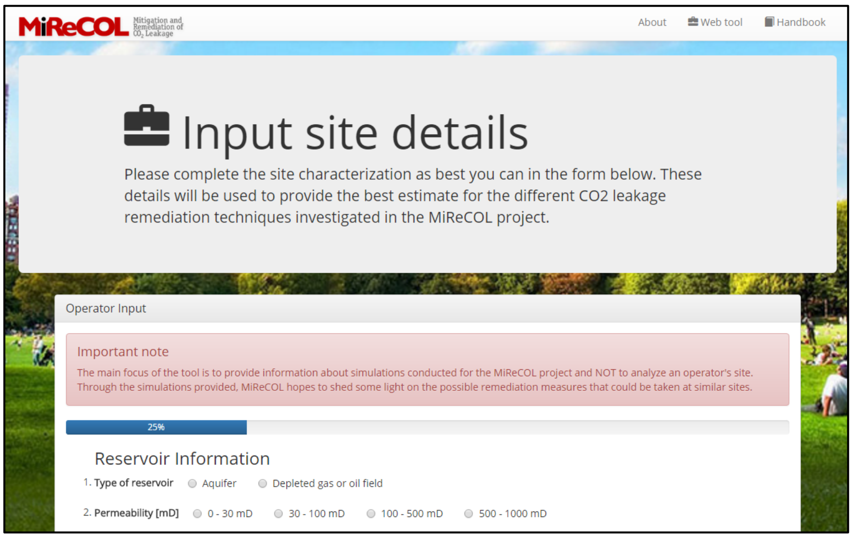


Figure 23. Example of the input for the site analysis page of the site remediation tool.

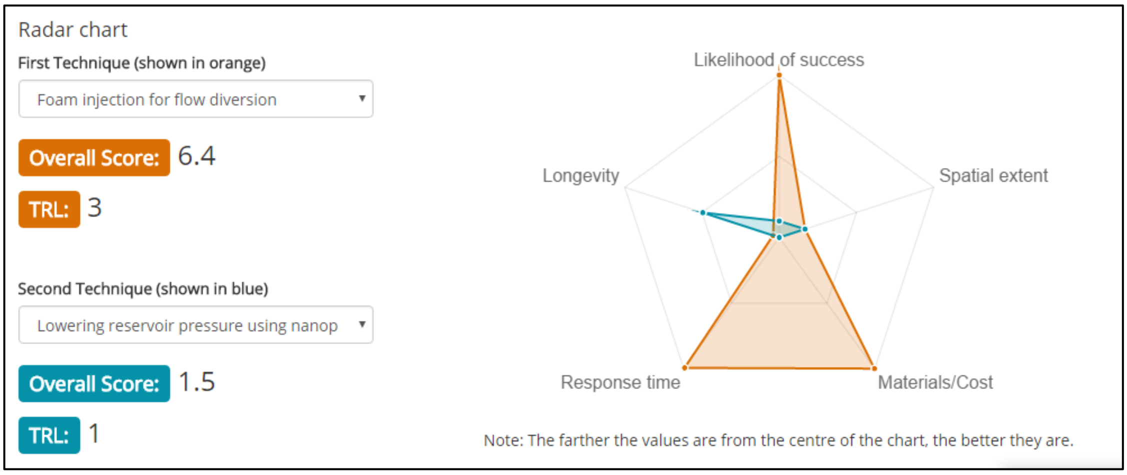


Figure 24. Output results from the site remediation portion of the web tool.

The “Well Remediation” selection will take you to the assessment of a leakage via a well barrier failure. This allows you to look into the possible leakage pathways in a well, learn about the specific components that could break, and then the common practices to remediate that component.

Overall, the main accomplishments of this part of the MiReCOL project have been the full development of the web tool and handbook, as well as the integration of the results into these two parts of the website. They will continue to be hosted online until February of 2022.

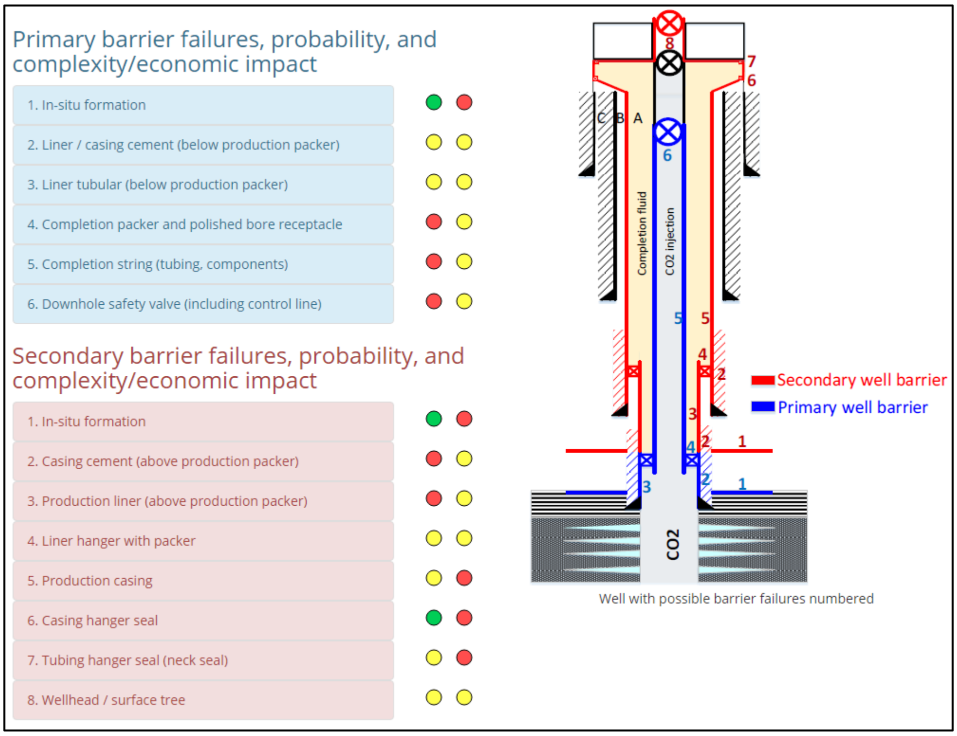


Figure 25. Image from the well remediation tool to identify the potential leakage barriers.

7 CONCLUDING REMARKS

The EU FP7 MiReCOL project aimed at developing a handbook of corrective measures that can be considered in the event of undesired migration of CO_2 in deep subsurface reservoirs. MiReCOL results support CO_2 storage project operators in assessing the value of specific corrective measures if the CO_2 in or near the storage reservoir does not behave as expected. The general scenarios considered in MiReCOL are 1) loss of conformance in the reservoir (undesired migration of CO_2 within the reservoir), 2) natural barrier breach (CO_2 migration through faults or fractures), and 3) well barrier breach (CO_2 migration along the well bore).

The project results include a series of technical reports and publications about specific correctives measures that act in or near the storage reservoir, an overview of measures that can be applied in the shallow subsurface, a measures portfolio analysis and, finally, a web-based handbook and tool that present all these results to operators and regulators.

The results of the project will be available online to CCS project operators and regulators. The results, together with material available in the open literature, could form the basis for the construction of a corrective measures plan, or for discussions between operator and regulator in the event of non-conformity in a storage project. Whatever the application of the project results, the MiReCOL project has advanced the understanding of corrective measures for CO_2 storage projects.

IMPACT EU FP7 MiReCOL

1. Socio-economic impact

The MiReCOL project will have impact on several levels, deriving from its contribution to the definition of protocols and safety regulations (i.e., corrective measures plans).

1. Site operators will be able to more efficiently define a corrective measures plan (pursuant to the EU Storage Directive), using the technical reports from MiReCOL and using the web-based tool and handbook.
2. In the event of an irregularity during an injection process, the results produced by the MiReCOL project will help to inform regulators of the options open to operators, in a technical sense, and will help them to understand the impact of each option in terms of effort, materials needed, cost and (environmental) impact.
3. A clear description of the impact and practical implementation of corrective measures will help local authorities understand their role in a CO_2 storage project, as it will help them to prepare safety regulations and protocols.
4. The better understanding and broader knowledge base for corrective measures improves the basis for the development of full-scale CCS project, which is one of the targets defined in the Declaration of Intent on CCS (https://setis.ec.europa.eu/system/files/integrated_set-plan/setplan_doi_ccus-final.pdf). In this way, MiReCOL supports the goals of the SET-PLAN.
5. The development of CCS has been strongly supported through a long series of research projects, funded through consecutive Framework Programs, which addressed different aspects and elements of the CCS chain. While the basis of knowledge and expertise in the Member States has thus been steadily growing, the support of CCS projects with the public has not been growing at the same rate. There is public opposition to geological storage of CCS, which, in part, is due to insufficient understanding of the process and the short-term and long-term safety and security. While recent and on-going projects address aspects of these issues, such as long-term security of storage, the short-term safety and controllability of storage is an aspect of CCS where clarity on the options open to operators to act in case of undesired events may help increase public confidence in CCS as a safe emission reduction technology. This is where the MiReCOL project will have impact.
6. The MiReCOL project will actively contribute to the implementation of the Roadmap and Implementation Plan of the CCS Industrial Initiative of the SET-Plan, and should, whenever relevant, contribute to the monitoring and knowledge sharing schemes of the Initiative.

2. Wider societal impact

The MiReCOL project will have the desired wider impact with the following strategy.

1. Increasing public confidence in CCS as a safe technique for CO_2 emission reduction is done through the publication of the non-technical reports. Dissemination of the results to the general public will be done by the project's primary audience of regulators, site operators and NGOs, who will be able to use our results to inform the general public.
2. Support site operators to efficiently design a corrective measures plan. Unfortunately, few CO_2 storage sites existed during the project's lifetime, or when the project ended. Two UK large-scale CCS projects were cancelled before the project was finalized; these projects would have been key users of the project results. At the time the project was finalized, the Maasvlakte CCS project in Rotterdam was still awaiting the decision to start.
3. Support site operators and regulators in the event of an irregularity during the injection process. Both technical and non-technical guidelines reports serve this goal; site owners in

Europe (Statoil in Norway) are aware of the project's results and associated partners in Australia and North America have been sent the project's final report

4. Support local authorities with a clear description of the impact and practical implementation of corrective measures to understand their role in a CO_2 storage project, as it will help them to prepare safety regulations and protocols. The non-technical report will focus on the impact of both leakage events and corrective measures on the surface environment. This informs local authorities about required actions in the case of a leakage event.
5. Contribute to the implementation of the Roadmap and Implementation Plan of the CCS Industrial Initiative of the SET-Plan. By providing a comprehensive description of existing corrective measures, by exploring and reporting on a number of new techniques will this project provide for and broaden the basis of an improved controllability of CO_2 storage projects. This supports the roll-out of CCS in Europe, as well as in other parts of the world, as the results of MiReCOL will be published after the project ends.

The technical reports, conference presentations and the workshops organized during the project will also support the impact at these levels. The table below summarises this (cmp = corrective measures plan).

	Increase public confidence	Support site operators (cmp)	Support site operators and regulators	Support local authorities	Contribute to implementation SET-PLAN
Technical guidelines report		X	X		X
Non-technical guidelines report	X		X	X	X
Web-based corrective measures tool	X	X	X	X	X
Technical reports and publications on specific corrective measures		X	X		X
Conference presentations (technical and non-technical)	X	X	X		X
Workshops (technical and non-technical)	X	X	X	X	X

3. Main dissemination actions

The foreseen dissemination activities and initiatives which will take place during the course of the project are:

- Handbook ('Guidelines'): the main project result is the online handbook with guidelines about the feasibility of corrective measures. The handbook discusses both existing and new corrective measures, the approach to assessing the feasibility of applying corrective measures in the case of leakage or threat. The handbook is available on the project web site.

- Web-based tool: an online web-based tool improves the dissemination and application of the results from the MiReCOL project. The public project web site hosts the online MiReCOL tool, that serves several purposes. As a first goal, the tool will help future site operators in setting up a corrective measures plan. Secondly, the tool will support operators and regulators in the event of an 'irregularity' at a site, by providing a short list of tools that can help mitigate or remediate the problem. Finally, the tool demonstrates to regulators, as well as the wider public, that techniques are available to minimize the effect of an unexpected event.
- The existence of the tool will be published broadly by advertising it in the IEAGHG Newsletter and through a link on the IEAGHG web site. This link will be placed close the monitoring tool that is also available through the IEAGHG website.
- Publications: Results from the project have been presented as scientific publications in conferences and peer-reviewed journals. These publications are available through the public project web site.
- Presence at conferences: MiReCOL results have been presented at conferences. The conferences were oriented at the technical community. At several conferences, presentations from the MiReCOL project filled one or more sessions.
- Workshops: During the project period, several workshops were held to discuss progress, the set-up of the web-based tool and handbook. One workshop was set up during the CO2Geonet Open Forum in Venice, where the scientific community in Europe meets with industry representatives to discuss progress in CCS.
- Partner network communication: The MiReCOL project has been promoted by the partners in the project.
- Website: unrestricted information about the MiReCOL project will remain accessible after the project end from the project website, www.mirecol-co2.eu. The website has been continuously updated with reports and information on the progress and results of the project; new publications after the project end will be added. The website will be a vital source for information about MiReCOL results, and will ensure access to public reports after the project has been concluded.
- Communication with the broader public: Partners of the consortium will, in addition to the above mentioned dissemination activities contribute with dissemination to the public by writing popular science articles and take part in interviews, panel discussions. etc.

4. Exploitation of results

The results from the MiReCOL project are primarily aimed at (future) site operators and regulators, at local authorities and, as a secondary audience, the general public. The aim of the project results is to clearly describe the knowledge base for corrective measures in a CO_2 storage project and, hence, to support the development of CCS; the web-based MiReCOL tool is a clear example.

The results of the project have been and will be published in the form of technical and non-technical project reports, scientific publications and conference papers, all of which are open. All public MiReCOL reports are available on the project website, www.mirecol-co2.eu.

The results of the project are of direct use to the partners in the project. The industrial partners, who are potential future CO_2 storage site operators, have provided their comments and suggestions for the development of the web-based tool. Unfortunately, the recent cancellation of the UK CCS competition resulted in the cancellation of two CCS project developments in the short term. Currently, the ROAD project (The Netherlands) is the only full-scale CCS project that is planning to start construction and operation in the short-term; partners in the MiReCOL consortium are closely linked to the ROAD project and will support the use of MiReCOL results in the ROAD project.

While no directly marketable products have been produced in the project, the work done in the project, such as laboratory tests and field experiments, has certainly advanced the status of ideas for new materials (gels, foams, cement, sealant). Partners in the project will use the results from the MiReCOL project in their further work. As an example, the promising results obtained in the Becej field test provide a good basis for further development of gel-based sealant, which could be used in future CO_2 projects.