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MiReCOL – A handbook and web tool of remediation and corrective actions for CO_2 storage sites

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Abstract

The use of CO2 storage for carbon emission reduction is crucial to achieve climate change goals. This can be seen through the efforts governments and organizations are putting on carbon capture and storage (CCS), such as at the recent climate talks in Paris (COP21) and reports from the International Panel on Climate Change (IPCC). Along with the push for CCS comes the requirement to ensure the safe and secure implementation of underground CO2 storage in order to gather support from governments and the public. The Mitigation and Remediation of CO2 Leakage (MiReCOL) project is designed to address this issue. MiReCOL is intended for CO2 storage operators and regulators and provides analyses of mitigation and remediation techniques against various leakage mechanisms. The analyses include computer simulation, laboratory tests, and field tests in Ketzin, Germany, Bečej, Serbia and K12-B, The Netherlands and cover both new and existing mitigation techniques. The project culminates with the compilation of a handbook of corrective measures and web tool, which will serve as a resource for operators and regulators. The handbook and web tool will be based off of the research conducted on the leakage mitigation techniques and the results obtained.

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Keywords: MiReCOL; CCS; remediation; mitigation; web tool; handbook

1. Introduction

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 [1] [2]. Integrated projects are currently in operation in various parts of the world [3]. 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. This project will support creating such corrective measures plans and will help build confidence in the safety of deep subsurface CO_2 storage, by laying out a toolbox of techniques available to mitigate and/or remediate undesired leakage of CO_2.

Concern about risk of CO_2 is not exclusive to recent years; much research on remediation has already been invested in CCS remediation. The IEA GHG produced a report on remediation of CO_2 storage sites in 2007, mapping out the possible leakage scenarios out of a reservoir and proposing remedial measures corresponding to those scenarios [4]. A major research project has been the CO_2 Capture Project, which has completed its third phase in 2014. This phase resulted in a collection of reports about

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the capture process and storage monitoring and verification of CCS [5]. Another method which has been used to address risk of CCS is assessment tools. One example of these is the online Monitoring Selection Tool, hosted by the IEA GHG [6]. This tool assists operators in designing a monitoring plan through the input of the operator's site. Another risk-based tool is from the National Risk Assessment Partnership and takes in the user's site characteristics to analyze the risk of CO_2 storage over time [7]. Such studies and tools play a valuable role when creating the required contingency plans for CCS projects, such as the contingency plan for the ROAD (Rotterdam Capture and Storage Demonstration Project) project in Rotterdam [8].

2. The MiReCOL project

The EU Storage Directive 2009/31/EC [9] 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*".

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. The scope of MiReCOL includes those corrective measures that can be applied after a significant irregularity is detected, in or around the storage reservoir: this includes the reservoir and cap rock, the overburden, and the wells [10].

The MiReCOL project consists of sensitivity studies on a series of corrective measures and lab tests of materials. The purpose is to better understand the potential impacts of the remediation techniques. Undesired migration of CO_2 could be within the reservoir, out of the reservoir via faults and fractures, or out of the reservoir along the well bore. The topic of the studies conducted include conventional remediation techniques, such as squeeze cementing, as well as more novel techniques, such as nanoparticle injection to accelerate convective mixing. Results from the project have been published elsewhere [11] [12] [13] [14] [15] [16] [17] [18] [19] [20] [21].

This project culminates with the compilation of a handbook, which serves as an accumulation of all the research performed during this project, as well as the development of a web-based tool. This tool offers estimates and examples of remediation options based on user input and is a useful platform to inform operators, regulators, policy makers, and the public on the risks behind addressing subsurface CO_2 migration (located online at tool.mirecol-co2.eu [21]).

Section 3 details the MiReCOL handbook, while Section 4 explains the interactive web tool and Section 5 gives an example of the web tool. The discussion and conclusion follow.

3. Handbook

The handbook for the MiReCOL project is the collection of the individual reports from the entire project. Each deliverable is organized within the handbook based on the remediation technique. On the project web app, the handbook is divided into three sections: remediation techniques, MiReCOL reports, and downloadable literature. The former contains a list of the different remediation techniques investigated with information about the process and risks of each technique. Topics covered in this part of the handbook are an overview of the remediation technique, the method to perform the technique, materials required (to aid the operator in estimating costs), associated risks and impacts of the technique, situations where this technique is applicable, case studies performed, and links to the MiReCOL reports related to the technique (see Fig. 1). The second section of the handbook consists of the project deliverables, some of which discuss more than one remediation technique. This part of the handbook shows the abstracts for the different deliverables and provides the option to view and download the deliverables (see Fig. 2). The third section of the handbook displays a list of links to the literature produced from the project, including published papers and research reports (see Fig. 3).

4. Web tool

The web tool is based on the scientific studies conducted for the MiReCOL project. These studies contribute to either the site remediation half of the web tool – which deals with unwanted CO_2 migration in or around the reservoir – or the well remediation half of the web tool – which deals with unwanted CO_2 migration within or out of a well (Fig. 4). The site remediation tool has been designed in a way to roughly compare the various remediation techniques across several common criteria based off of user input. The well remediation tool offers available practices based off of the failed component in the user's well. Both parts of the web tool assume that the user has recognized a significant irregularity at their site already. The following sections go into more detail about these two elements of the web tool.

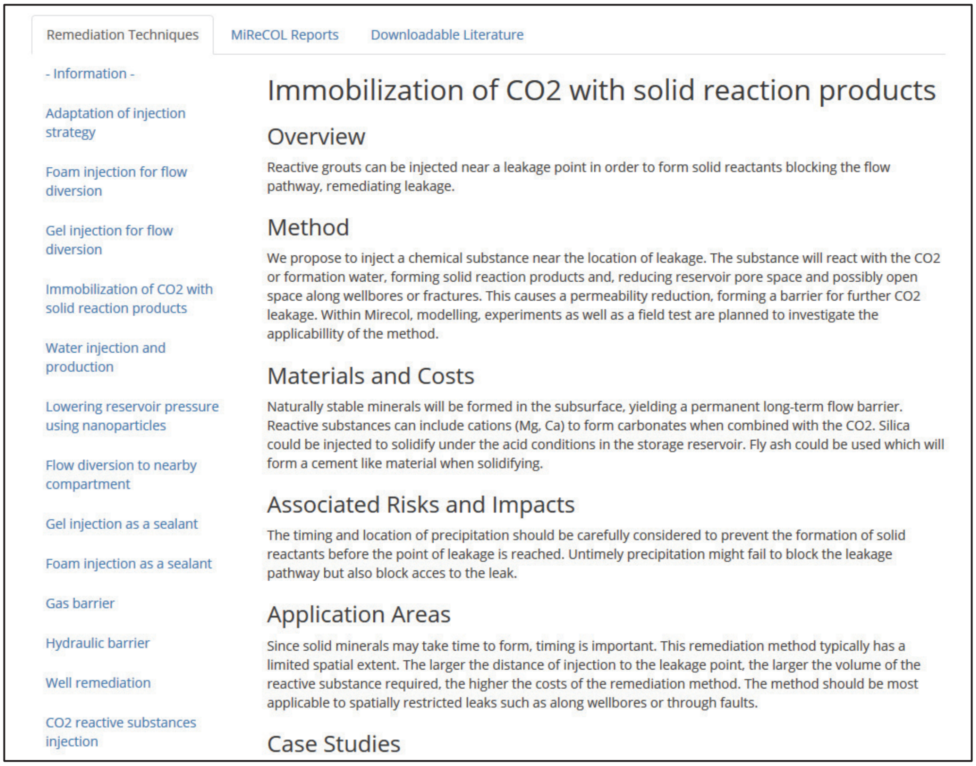

Fig. 1. Screenshot of the Remediation Techniques section of the handbook found in the MiReCOL web app. A list of remediation techniques is located in the left column, while the right column displays information about the technique.

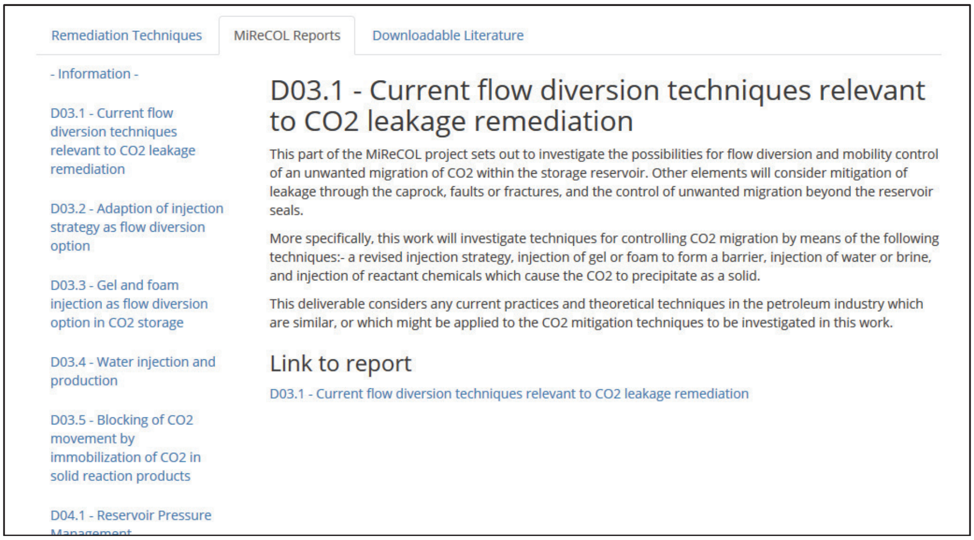

Fig. 2. Screenshot of the MiReCOL Reports section of the handbook found in the web app. A list of deliverables for the project is located in the left column, while the right column displays the selected deliverable abstract and hyperlink to the report.

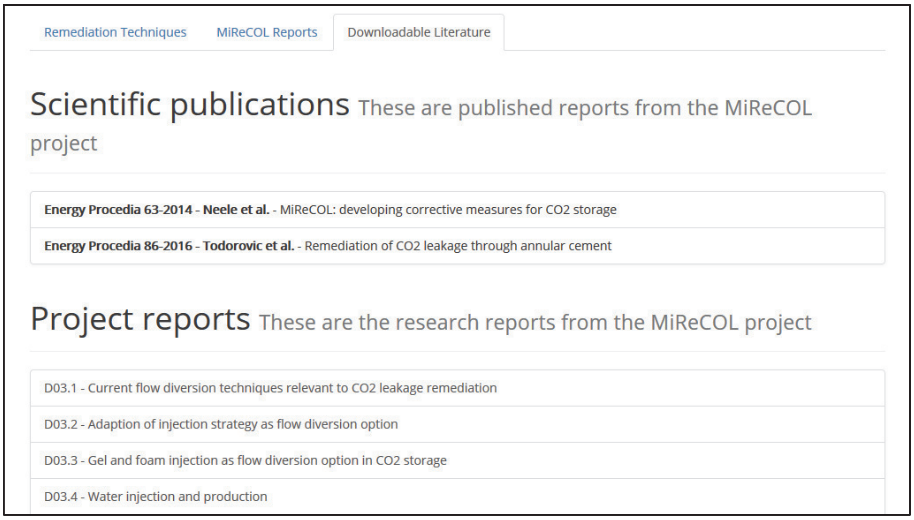

Fig. 3. Screenshot of the Downloadable Literature section of the handbook found in the web app, displaying links to published papers and research reports from the MiReCOL project.

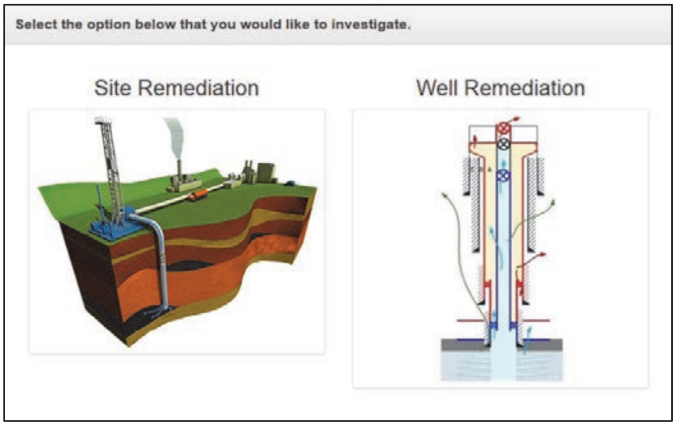

Fig. 4. Screenshot of the MiReCOL website displaying the two parts of the web tool: the site remediation tool and the well remediation tool.

4.1. Site remediation tool

4.1.1. User input

The user input for the site remediation tool consists of questions about the user's CO_2 storage site. These questions are based on the scientific studies of the project. For each remediation technique, the project scientists determined which site characteristics had a noticeable effect on the results of their particular MiReCOL study. Depending on the question type (i.e., binary, numerical, or categorical), appropriate options for these site characteristics are displayed on the website for the user to select. All of these site characteristics are organized by category and subsequently compiled into a list on an online form for the user to complete (Fig. 5). The categories for these characterization questions are reservoir information, CO_2 storage information, migration information, well information, and mitigation information. Once the user completes the form to the best of their knowledge, they submit the form to continue to the output page, and their set of answers to the questions becomes the "user scenario".

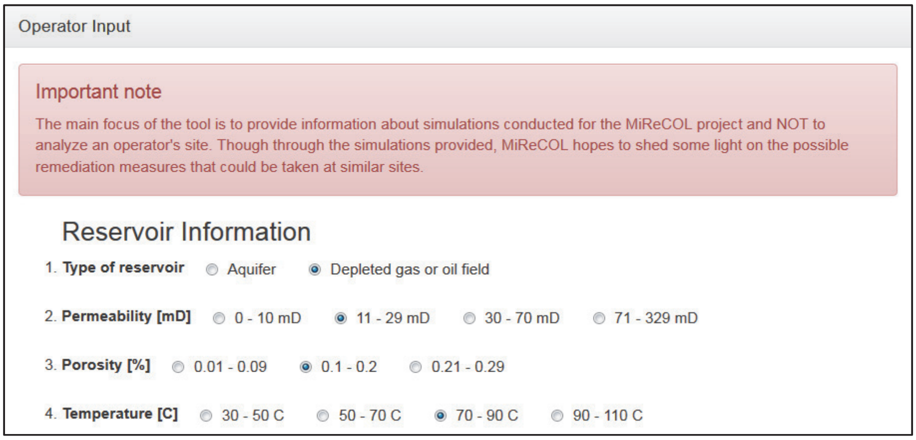

Fig. 5. Screenshot of the MiReCOL web tool showing how the user inputs site characteristics.

4.1.2. Output

Each corrective measure studied within MiReCOL has different types of results. In order to easily compare the different remediation techniques, five output criteria were selected to be used in the site remediation tool:

1. Likelihood of success,
2. Spatial extent of the remediation,
3. Required components of the remediation,
4. Response time of the remediation, and
5. Longevity of the remediation.

The values for each of these five outputs are based on scientific output for each set of site characteristics they tested, with each set of site characteristics varying depending on remediation technique. This set of site characteristics is called the scientific scenario. The scientific scenarios vary between remediation techniques because different site characteristics influence different remediation techniques. To provide an example, take the remediation technique of using foam to stop migration at the leakage site shown in Table 1. The relevant site characteristics are listed in the leftmost column, while two scientific scenarios out of many are displayed to the right. To make these numerous scientific scenarios, the scientists varied the relevant site characteristics between realistic values, and then produced results for each of these scientific scenarios. In this way, many scientific scenarios (each with output values) are provided without having to do computationally intensive modeling within the web tool.

Table 1. Example of site characteristics and scenarios that are compared with the user input scenario for the remediation technique of using foam to stop unwanted CO_2 migration.

Relevant Site Characteristic	[units]	Scenario 1	Scenario 2	Scenario …
1. Permeability	[mD]	20	50	…
2. Leakage rate	[Sm^3/day]	100	200	…
3. Dip angle	[^{o}]	5	5	…
4. Depth	[m]	3,000	3,000	…
5. CO_2 in place	[Mt]	10	10	…
6. Permeability variation coefficient	[-]	0	0	…
7. Porosity	[-]	0.15	0.15	…
8. Gas injection rate	[Sm^3/day]	100,000	100,000	…
9. Leak distance from injection site	[m]	375	375	…
10. Foam injected	[kg]	310,000	1,500,000	…

The user input, or "user scenario" explained in Section 4.1, is then compared to every scientific scenario. The most similar scientific scenario for each remediation technique and its corresponding output are displayed to the user. The user can see how close their own scenario is to the selected scientific scenario.

The manner in which the comparison is made is through the use of Gower's general coefficient of similarity [22]. This calculation compares two sets of data, resulting in a value between 0 and 1, with 1 being perfect similarity and 0 being perfect dissimilarity. The calculation of this coefficient takes into account the type of data as well: if the data are quantitative, it calculates how close the two numbers are based on the range of that site characteristic, and if the data are qualitative or binary, it calculates if the data match or not. A weight for the site characteristic can be provided in case the scientist believes that a certain site characteristic is more influential than another. The remediation scenario with the highest coefficient of similarity to the "user scenario" is chosen and the output of that remediation scenario is displayed on the output page of the remediation site tool.

The five output values (likelihood of success, spatial extent of the remediation, required components of the remediation, response time of the remediation, and longevity of the remediation) for each remediation technique are then displayed on the output page in the form of a radar chart, along with an overall score. The radar chart is a visualization to compare two remediation techniques, based on the five output values. Using the mouse to hover over the outputs on the radar chart offers a value normalized to a 10-point scale. The larger the area of the chart, the better the output values are (e.g. a large area would mean high likelihood of success, high spatial extent of remediation, low cost, short response time, and high longevity). The overall score is a summation of the five output values, normalized to a 10-point scale. These two features can be seen in Fig. 6. Also shown in this figure is the listing of the user's scenario, as well as the selected scientific scenario for each remediation technique.

The five outputs for each remediation technique are listed lower on the output page in the site remediation tool (see Fig. 7). Also provided are the associated risks with the remediation technique and links to the relevant MiReCOL reports. The remediation techniques are separated into appropriate methods and inappropriate methods. If the technique is inappropriate, then the reason why is provided. For example, if the remediation technique is to divert the CO_2 to a neighboring storage compartment yet there is no neighboring compartment, then the remediation technique would be deemed not applicable.

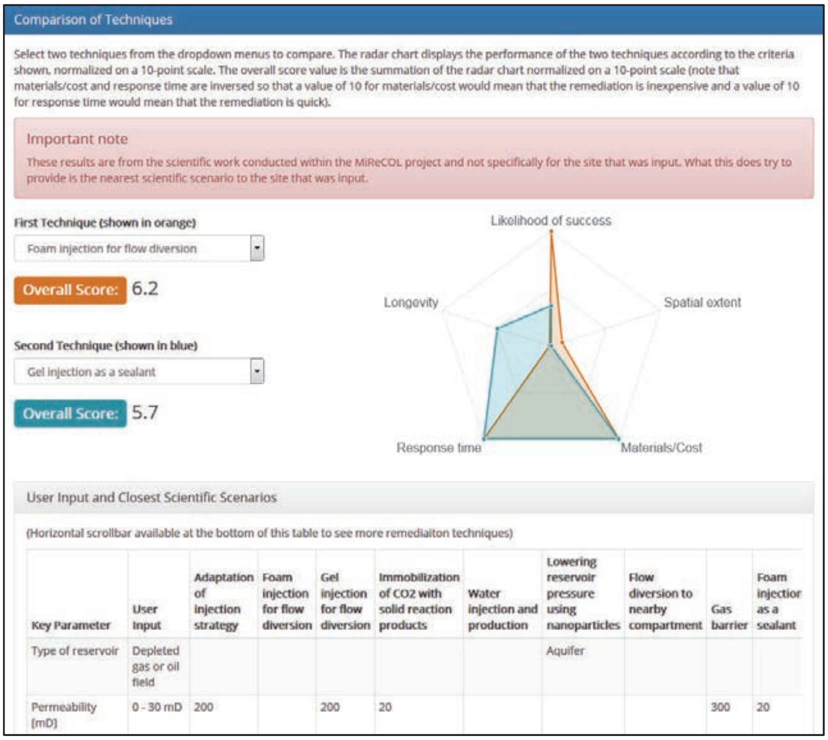

Fig. 6. Screenshot of the radar chart and the overall score on the output page of the MiReCOL site remediation tool.

4.1.3. Tool demonstration

To provide a more coherent explanation of the web tool for site remediation from the perspective of the user, this section follows one example user. To begin, the user inputs their site characteristics to the web tool, as shown in Fig. 5. A selection of the site details that the user has input to the web tool are listed Table 2.

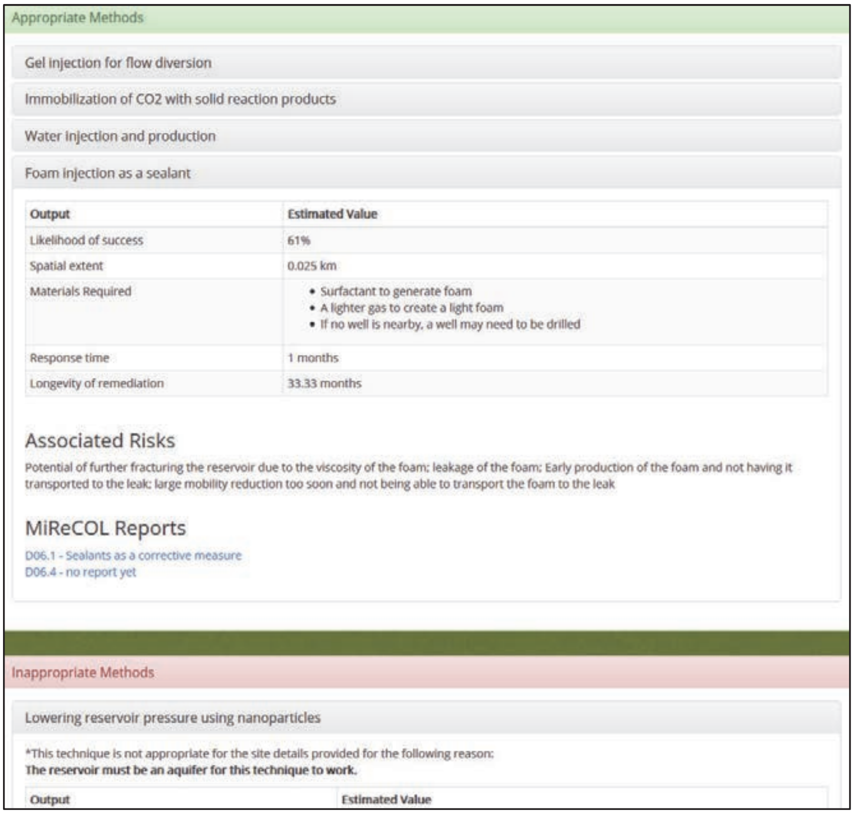

Fig. 7. Screenshot of the output page on the MiReCOL site remediation tool showing the organization of remediation techniques that are appropriate for the user input and not appropriate.

Once the site characteristics have been input, the user is directed to the output page, shown in Fig. 6 and Fig. 7. By selecting two techniques from the two dropdown menus, the user can view the radar diagram to visually compare the two based on five criteria: likelihood of success, spatial extent, materials required/cost, response time, and longevity of remediation. Lower, the user can view their own input as well as the scientific scenarios from each remediation technique that are closest to their own input. Further down the page, the user can view which techniques are applicable and which aren't, according to their site characteristics (Fig. 8). Under each inappropriate method, a reason for why the remediation technique is not appropriate is listed. The technique of "lowering reservoir pressure using nanoparticles" is not appropriate because the user selected "Depleted gas or oil field", while this technique requires a reservoir in order for it to work. As for the second in the list, "Flow diversion to nearby compartment", the user said there was no adjacent compartments at his site, thus this technique would not work either.

Table 2. An example user's site characteristics that are input into the MiReCOL site remediation web tool.

Site Characteristic	[units]	User Scenario
1. Type of reservoir	[-]	Depleted gas or oil field
2. Permeability	[mD]	0 – 30
3. Porosity	[%]	0.1 – 0.2
4.Temperature	[C]	50 – 70
…		
9. Adjacent compartments	[-]	No
…		
25. Leak distance from injection site	[m]	0 – 10

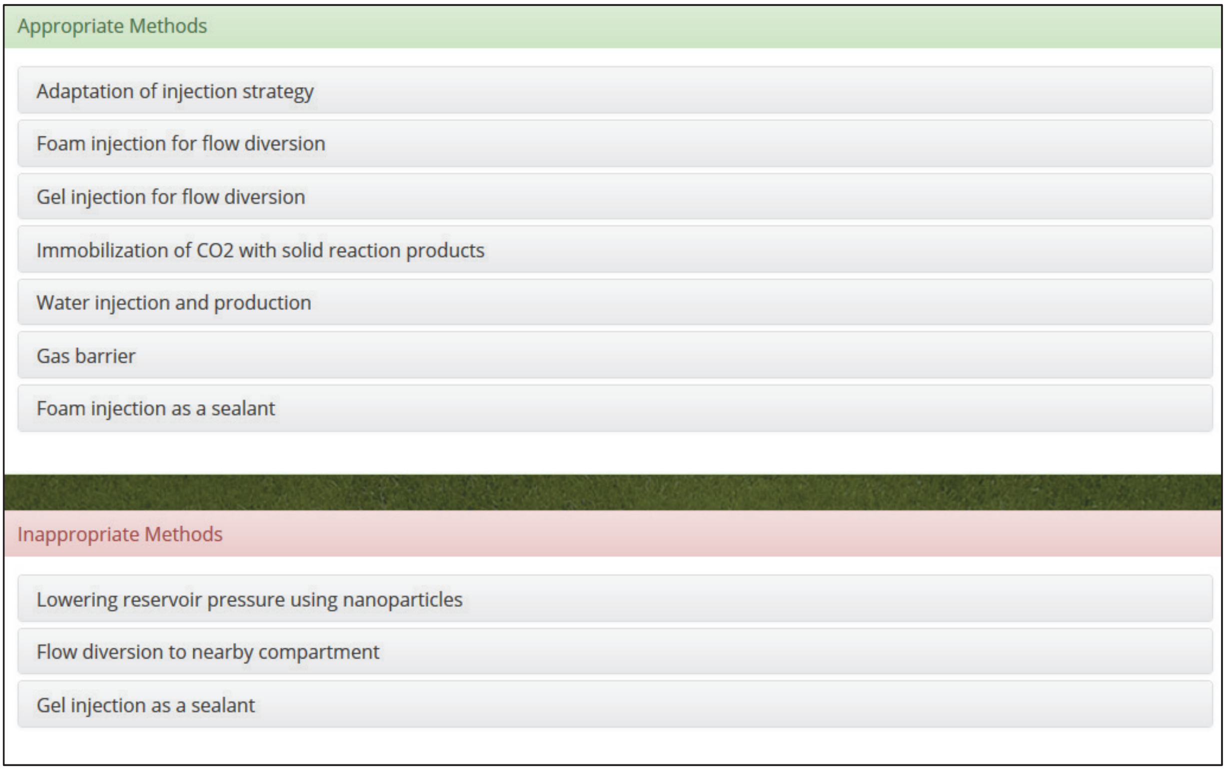

Fig. 8. Screenshot showing the appropriate and inappropriate remediation techniques.

The remaining outputs for each method are displayed in Fig. 7, which shows the same five criteria as in the radar diagram, along with associated risks and reports. For the technique “Foam injection for flow diversion”, the scenario estimates about 60% likelihood of success; about 25 m of spatial extent of the remediation; a requirement of surfactant, a lighter gas, and possibly drilling a well; a response time of about 1 month; and a longevity for over 2 years. Associated risks are

> *Potential of further fracturing the reservoir due to the viscosity of the foam; leakage of the foam; early production of the foam and not having it transported to the leak; large mobility reduction too soon and not being able to transport the foam to the leak.*

Lastly, links to two reports are listed, deliverables 6.1 and 6.4 of the MiReCOL project.

4.2. Well remediation tool

4.2.1. User input

The structure of the well remediation tool is based on the possible barriers that could fail in a well. These are listed under the headings of primary and secondary barriers, and are associated with a traffic light circle for both probability and complexity/economic impact of the barrier failure (see Fig. 9). The green carries a positive meaning, yellow an uncertain meaning, and red a negative meaning. Once a barrier is selected, then a small information screen on the barrier appears, describing the barrier and possible causes of the barrier. From here, the user can either select this barrier as the failed component, or close the information screen and return to the overall list of barriers.

4.2.2. Output

Once the user selects the failed barrier, remediation practices for that specific barrier are presented. Below these practices, associated technical risks and economic risks are provided. These are based off of the TECOP methodology: Technical risks, Economic risks, Commercial risks, Operational risks, and Political risks. As the latter three risk categories are highly site dependent, they must be assessed by the individual user and are not provided by the tool. These risk categories are given a traffic light coloring scheme as well, where green signifies little risk, yellow signifies a medium amount of risk, and red signifies more serious risk. A sample of the format for the well remediation output page can be seen in Fig. 10.

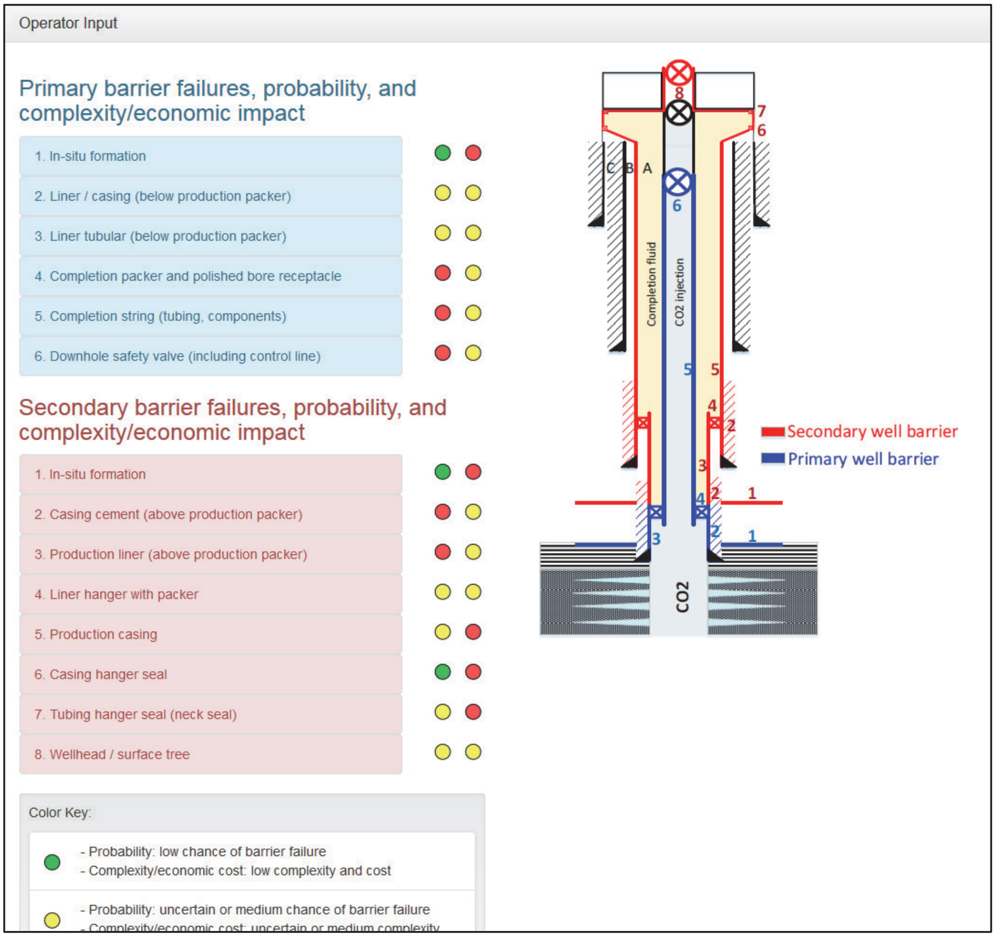

Fig. 9. Screenshot of the MiReCOL well remediation tool, showing the possible primary and secondary barriers and the traffic lights for probability and complexity/economic impact.

5. Discussion

The primary intent for the web tool and handbook components of the MiReCOL project is provide insight into the applicability of a range of corrective measures to a specific site or case of undesired migration of CO_2 (located online at tool.mirecol-co2.eu [21]). The handbook provides the user with a set of detailed reports on a range of corrective measure techniques that deal with the storage reservoir, cap rock, faults, and wells. The web tool graphically presents the results from the analyses of the range of corrective measures. The web tool helps the user to view and understand the impacts of remediation techniques for a specific case of undesired CO_2 migration.

The MiReCOL web app fills the absence of remediation and mitigation support for CO_2 leakage. This information collected in the web app is beneficial for both CO_2 storage operators and for regulators. Other stakeholders to whom this pool of knowledge is valuable are the public and decision-makers, as this is an accessible manner to learn about CO_2 leakage remediation and mitigation.

More specifically, the handbook has several uses among the various stakeholders. For CO_2 storage operators, the handbook provides a reference when developing a corrective measures plan, which is necessary when applying for the CO_2 storage application. The content of a corrective measures plan includes what the operator intends to do if ever there is a threat to or leakage of the CO_2 storage site. The handbook can be a reference for the operator in case of actual leakage, or when a significant irregularity in the CO_2 storage site is noticed. It provides a single location to view the impacts of many different CO_2 remediation techniques. This handbook can be utilized by regulatory authorities who need to be aware of the options a CO_2 storage operator has available when responding to a significant irregularity at their storage site, both for the corrective measures plan and in the case of an actual irregularity. Finally, relevant authorities, the public, and decision makers can make use out of the handbook when interested in learning about the implications of remediation of a CO_2 storage site. By referencing this collection of studies, they can educate themselves on the risks and impacts of various remediation techniques. This handbook places operators, authorities, decision makers, and the public on the same level when considering the options for remediation and mitigation of CO_2 storage leakage.

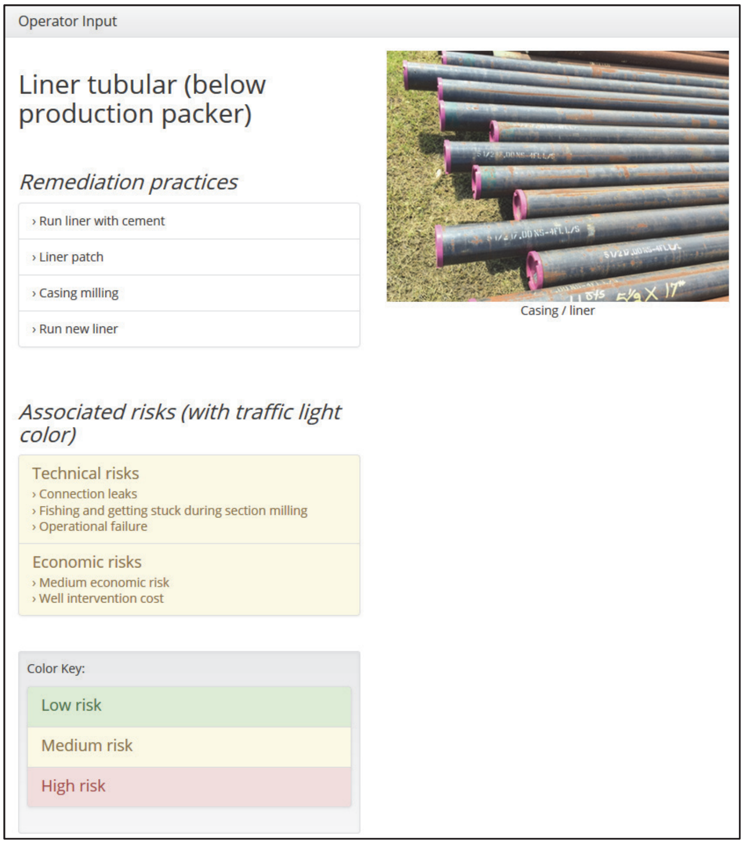

Fig. 10. Screenshot of the output for the MiReCOL well remediation tool. Once a well barrier is selected by the user, this page displays the common remediation practices and the associated technical and economic risks, with traffic light colors corresponding to the severity of each risk.

The counterpart of the MiReCOL handbook provides important functions for these same parties. The web tool serves an obvious role for storage operators, again in assisting them in developing their corrective measures plans as well as in the actual case of unwanted CO_2 migration. The tool provides more specific details than the handbook, as it displays scenarios for each corrective measure and places the remediation techniques into either the applicable or not applicable category. These specific scenarios suggest to the operator the most feasible remediation technique in terms of criteria such as likelihood of success and longevity of remediation, thus enabling the operator to make an informed decision regarding actions toward their storage site. As with the handbook, the web tool has the potential to inform regulators, the public, and decision makers on specific scenarios for the various remediation techniques. The scenarios attach a more tangible meaning to the remediation techniques and form a helpful interface to the analyses presented in the scientific reports.

The web tool provides limited site-specific information for the user. The tool contains tabulated results for each corrective measure and selects those results that are most relevant for the user-specified case. Therefore, the output criteria (e.g. likelihood of success and response time) that are displayed should be interpreted as estimates for the case at hand. The main purpose of the tool is to provide insight into the applicability of a range of corrective measures.

6. Conclusions

The web tool and handbook that form the MiReCOL web app are designed to translate scientific experimentation and research on new and existing corrective measures for CO_2 storage projects into an accessible medium to inform and assist all parties involved in CO_2 storage. The handbook is useful for referencing the remediation studies conducted within the project, while the tool is useful in examining remediation options for a CO_2 site or well. The tool is based off of scientific experimentation of a range of remediation techniques, with the output of the tool being the applicability of each remediation technique on a user-specified site along with comparable criteria (such as response time and longevity of the remediation method). When using the tool for well remediation, the failed well component is selected and risks and remediation measures are displayed. The handbook and web tool provide quick access to the performance and risks of a variety of remediation techniques, useful particularly for operators when designing and implementing a contingency plan.

Limited tools exist in providing information about CCS remediation techniques, which is where the utility of the MiReCOL web app can be found, as it packages analyses in a valuable way for storage operators and regulators. Building on a large number of scenarios input by the project scientists and experts (which are not commonly found in scientific publications), the web tool offers a quick comparison of the impacts of the various remediation techniques. The web app serves as a single location to find practical information on remediating a CO_2 storage site, with the potential to be expanded when further remedial measures are studied. This resource enables operators and regulators to better plan against risks, make informed decisions when remediating storage sites, and formulate guidelines, regulations, and protocols around CO_2 storage

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