Recommendations for research to support CCS deployment in Europe beyond 2020

Update on CO$_2$ Transport and Storage
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This document has been prepared on behalf of the Advisory Council of the European Technology Platform for Zero Emission Fossil Fuel Power Plants (ZEP). The information and views contained in this document are the collective view of the Advisory Council and not of individual members, or of the European Commission. Neither the Advisory Council, the European Commission, nor any person acting on their behalf, is responsible for the use that might be made of the information contained in this publication.
1 Introduction

The critical role of CO₂ Capture and Storage (CCS) in meeting the EU’s energy, climate and societal goals is now indisputable: the European Commission’s Communication on CCS¹ has confirmed that it is not only “vital for meeting the Union’s greenhouse gas reduction targets”, it provides a “very visible link between jobs in local communities and continued industrial production”. Indeed, by 2050 CCS must account for ~20-30% of total emissions reductions in the power sector alone, which means that “For all fossil fuels, Carbon Capture and Storage will have to be applied from around 2030 onwards”.

1.1 R&D plays a critical role in accelerating CCS deployment in Europe

In 2010, ZEP published its landmark report, “Recommendations for research to support the deployment of CCS in Europe beyond 2020”, which identified key R&D areas requiring support in order to drive down costs and accelerate deployment via well-targeted programmes. FP7-ENERGY calls have taken into account several key recommendations, proving various individual components of the CCS value chain. Much learning has been achieved and industry is today confident that CO₂ transport and storage can be safely introduced on a commercial scale.

However, further targeted R&D is essential in areas that can significantly reduce costs and commercial risks. ZEP has therefore published an update on R&D priorities for CO₂ capture, while this report covers R&D priorities for CO₂ transport and storage, taking into account advances achieved to date. (N.B. These are prioritised independently of the source of capture.) ZEP has also published a separate report outlining the urgent need for up to six new large storage pilots, EU-wide.

Work on R&D priorities must be initiated now and/or continued in order to enable the wide deployment of CCS by 2030. This includes all the key development steps (laboratory – small/large pilot – demonstration – pre-commercial). To this end, CCS must be fully represented in Horizon 2020 as a critical low-carbon technology for delivering EU climate goals.

1.2 Parallel European R&D initiatives ensure effective joint programming

In addition to ZEP, there are two other parallel initiatives for setting R&D priorities in Europe: the European Industrial Initiative (EII) on CCS and the European Energy Research Alliance (EERA) Joint Programme on CCS (CCS-JP) – see Figure 1.

![Figure 1: Parallel work on setting R&D priorities by EERA, ZEP and the CCS EII, under the ‘umbrella’ of the SET Plan Steering Group (SG)](http://setis.ec.europa.eu/set-plan-implementation/european-industrial-initiatives-eii/eii-implementation-plans)

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¹ http://ec.europa.eu/energy/coal/ccs_en.htm
³ www.zeroyemissionsplatform.eu/library.html/publication/95-zep-report-on-long-term-ccs-road
⁵ www.zeroyemissionsplatform.eu/library/publication/236-zepcapturereport.html, October 2013
1.3 R&D should now focus on improving efficiency and reducing costs

R&D projects to date have been effective in showing that CO₂ storage is safe and technically feasible. R&D must therefore now focus on improving efficiency and reducing the costs of CO₂ transport and storage – and the CCS chain as a whole.

Key remaining challenges and long-term R&D needs (where optimisation can be made) have been identified by ZEP building on experience from existing pilots and developing CCS demonstration projects. This includes the urgent need to build up to six large CO₂ storage pilots and overcome barriers to infrastructure development in order to create confidence in large-scale CCS.

ZEP recommendations are structured to follow the development stages of a storage project, including the linked delivery of CO₂ to a storage site:

- Exploration of storage sites
- Appraisal of storage sites
- Development of transport infrastructure and storage sites
- Operation: a) contingency measures to reduce project risks  b) processes for leakage scenarios  c) dynamics, monitoring and remediation
- Post-injection: monitoring and remediation
- Liability
- Plus CCU/CCUS⁷ options which could accelerate CCS deployment.

The aim: to address the main areas of uncertainty or optimisation where costs can be reduced. R&D needs for each step are summarised in sections 2.1-2.7. As there are a multitude of R&D topics, and pursuing R&D in all areas would be costly, an evaluation has been made as to which topics could have a positive impact on investment decision parameters considered by project developers. Some topics, of course, do not concern technology improvement and are therefore inappropriate for evaluation against cost efficiency or risk reduction. However, they are still important in that they will accelerate the delivery of commercial CCS projects.

It should be emphasised that conclusions and recommendations are based on estimates of the impact of R&D topics and the current level of knowledge within ZEP. For example, operability and availability are still to a large extent unexplored research areas.

1.3.1 Definition of timeframe

The timeframe for long-term R&D has been categorised in intervals according to the needs of the European energy system, i.e. by 2020, 2030 and beyond:

- **Period I, up to 2020:** as the availability of proven storage capacity is a prerequisite for any investment decision in commercial capture plants and transport infrastructure, the long-term R&D plan for transport and storage places emphasis on work to be conducted over the next 5-10 years.
- **Period II, 2020-2030:** second-generation technologies brought to commercial operation within this period are likely to be based on improvements and refinements of first-generation technologies used in Period I.
- **Period III, 2030 and beyond:** third-generation (long-term) technologies brought to commercial operation within this period are likely to be based on optimised and refined technologies from Periods I and II. In particular, demonstration phase technologies from Period II should become commercial.

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⁷ CO₂ Capture and Use (CCU), CO₂ Capture, Use and Storage (CCUS)
1.3.2 Definition of validation status

In Chapter 2, summary tables are provided where colour coding has been used to define the validation status of the technologies applied to the various project development phases. As in ZEP’s “Matrix of Technologies”, validation status is divided into three levels:

- **Green**  Fully validated: commercially available for application in large power plants
- **Yellow** Partly validated: ready for demonstration plants
- **Red** Not validated: not tested/less advanced than pilot scale. However, no key R&D needs have been identified.

1.4 Key R&D priorities for CO₂ transport and storage

Key R&D priorities for CO₂ transport and storage identified by ZEP include:

- Establishing up to six new large storage pilots EU-wide in order to accelerate state-of-the-art technology, drive down costs and increase public confidence in CO₂ storage.
- Developing CO₂ transport and storage network configurations in order to maximise economies of scale and build confidence in large-scale CCS infrastructure.
- Establishing common procedures for maturing CO₂ storage sites to the level where there is significant certainty of storage capacity.
- Providing project developers with a suite of contingency measures for the assessment of technical business risks.
- Developing key performance criteria for the guidance of project developers, regulators and policymakers.
- Reducing uncertainty regarding liability and the long-term performance of storage sites.
- Maximising the benefits of CCU/CCUS as an enabling technology for CCS, e.g. the combination of CCS with Enhanced Oil Recovery (EOR), geothermal heat production.

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The Zero Emissions Platform (ZEP)

Founded in 2005, the Zero Emissions Platform (ZEP) is focused on CCS as a critical technology for achieving Europe’s energy, climate and societal goals. A coalition of over 200 members from 19 countries — representing academics, scientists, European utilities, petroleum companies, equipment suppliers and environmental NGOs — ZEP serves as an advisor to the European Commission on the research, demonstration and deployment of CCS.

This report has been developed by experts in CO₂ transport and storage within ZEP’s Taskforce Technology; ongoing, parallel activities via ZEP’s membership of the CCS EII have also been taken into account.

www.zeroemissionsplatform.eu
2 Recommendations for research on CO₂ transport and storage

2.1 Reduce time for storage site characterisation

A wide range of CO₂ storage options exists across Europe. The FP7 CO2StoP project is currently building a second-generation database on storage potential for deep saline aquifers and hydrocarbon fields for policymaking purposes, based on national or regional updates since the FP7 Geocapacity project (first generation). Several other ongoing initiatives are also developing the knowledge base in certain regions, e.g. the UK continental shelf, the Norwegian sector of the North Sea and the Nordic region.

However, the resources available limit the ambition level. Yet it is essential that project developers have a tool for identifying and prioritising options for long-term CO₂ storage. A comprehensive, web-based European CO₂ storage atlas is therefore urgently required.

Key challenges and long-term R&D targets
- Integrate and standardise national approaches to estimations of storage capacities.
- Generalise and transfer knowledge from well-investigated sites to poorly-investigated geologies in order to obtain a regional coverage.

<table>
<thead>
<tr>
<th>Rank</th>
<th>Key R&amp;D needs: exploration of CO₂ storage sites</th>
<th>-2020</th>
<th>2020-2030</th>
<th>2030+</th>
</tr>
</thead>
<tbody>
<tr>
<td>PR</td>
<td>Reduce time required to characterise storage sites adequately. Classify storage sites in terms of a reserves maturation process similar to SPE petroleum maturation.</td>
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<td></td>
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</tr>
<tr>
<td>PR</td>
<td>Define key factors (spatial constraints) that affect the interaction between other subsurface resources. Allocation of pore space and resource interaction management.</td>
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</tbody>
</table>

Rankings: PR – Prioritised, M – Medium, L – Low
Colour codes: Green – Validated, Yellow – Partly Validated, Red – Not Validated

2.2 Establish common procedures for maturing storage sites

It is recognised in the oil, gas and mineral extractive industries that a set of common standard definitions is needed that can be applied consistently by international financial, regulatory, and reporting entities. The same is true for CO₂ storage resources, where an agreed set of definitions would benefit all stakeholders and provide greater consistency, transparency and reliability.

The key challenge is to establish common procedures for maturing CO₂ storage sites to a level where significant certainty of storage capacity exists, in line with the existing Petroleum Resources Management System which provides the basis for classification and categorisation of all petroleum reserves and resources. As well as qualifying individual storage sites, this information (in combination with the storage atlas) is also crucial for developing a European CO₂ transport infrastructure.

Key challenges and long-term R&D targets
- Establish common procedures for maturing CO₂ storage sites to the level where significant certainty of storage capacity exists.

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9 www.co2geonet.com/UserFiles/file/Open%20Forum%202012/Posters/CO2StoP%20poster%20Poulsen%20et%20al%202012.pdf
10 SPE (2011), Guidelines for Application of the Petroleum Resources Management System
<table>
<thead>
<tr>
<th>Rank</th>
<th>Key R&amp;D needs: appraisal of storage sites</th>
</tr>
</thead>
<tbody>
<tr>
<td>PR</td>
<td>Better near well-bore understanding and improved coupling of multi-phase flow, thermodynamics, geochemistry and geomechanics (including in faults and fractures). Of these two components, geomechanics (combined with geochemistry in certain reservoirs) are key.</td>
</tr>
<tr>
<td>PR</td>
<td>Validation of models, i.e. calibration, verification and sensitivity analysis of large-scale simulations. There is a need for real data sets/performance (i.e. at the time data is available from the operation of the storage pilots).</td>
</tr>
<tr>
<td>PR</td>
<td>Improve knowledge of hydraulic properties of faults (tight or not, methods, resolution): - Estimate fault permeabilities, fault development and induced seismicity during CO₂ injection at a fault permeability test site into a fault at realistic depths. - Study the coupling of geomechanical and geochemical processes, and the correlation between the seismic data and the energy injected.</td>
</tr>
<tr>
<td>PR</td>
<td>Strategies to define the storage complex</td>
</tr>
<tr>
<td>M</td>
<td>Storage appraisal and development strategies for early (post-demonstration) deployment</td>
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<tr>
<td>L</td>
<td>Benchmarking exercises to compare capabilities of different modelling tools and more clearly define the appropriateness of their application to specific storage issues</td>
</tr>
</tbody>
</table>

Rankings: PR – Prioritised, M – Medium, L – Low
Colour codes: Green – Validated, Yellow – Partly Validated, Red – Not Validated

### 2.3 Enable cost-efficient development of transport infrastructure and storage sites

#### 2.3.1 Transport infrastructure

A CCS cluster (i.e. the sharing of transport and storage infrastructure by more than one capture proponent and more than one storage proponent) provides a nucleus for ‘first mover’ projects to gain critical mass. Such clusters provide a platform for the wide-scale deployment of the CCS industry, benefitting significantly from economies of scale. Only when large volumes of CO₂ share a common infrastructure will the infrastructure costs per tonne come down.

There are technical blockers for infrastructure components, especially regarding technical regulations for pipeline integrity. Other issues occur due to different sources of CO₂, which results in the combination of different CO₂ qualities, different transport modes (e.g. ship or pipeline) and connected operational issues (e.g. the volatility of CO₂ production vs. possible continuity needs of storage sites, or challenges due to different physical conditions of CO₂).

In FP7, important CO₂ transport R&D has focused on key conditions needed to enable the large-scale deployment of CCS in the EU and techno-economic assessments of the impact of impurities in the CO₂ (fluid properties, phase behaviour and chemical reactions in pipelines). A key challenge is to incorporate these learnings into the development of transport and storage network configurations suitable for Europe.

#### Key challenges and long-term R&D targets

- Establish CCS transport and storage network configurations and build confidence in the infrastructure aspects of the operational performance of these chains.
### Key R&D needs: cost-efficient development of transport infrastructure

<table>
<thead>
<tr>
<th>Rank</th>
<th>Key R&amp;D needs: cost-efficient development of transport infrastructure</th>
<th>2020</th>
<th>2020-2030</th>
<th>2030+</th>
</tr>
</thead>
<tbody>
<tr>
<td>PR</td>
<td>Improve understanding of multi-phase flow</td>
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<tr>
<td>sPR</td>
<td>Develop conceptual design for offshore unloading/injection of CO₂ transport by ship (including compression to, for example, 100 bar)</td>
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<tr>
<td>PR</td>
<td>Risk assessment for CO₂ pipelines with a focus on cost-efficient mitigation measures and opportunities</td>
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<tr>
<td>PR</td>
<td>Integrity of large-scale CCS infrastructures: improve understanding of material issues, corrosion, solid formation and interaction of CO₂ on seals for both top-side and down-hole applications. Continued R&amp;D should focus on setting tolerances.</td>
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<tr>
<td>PR</td>
<td>Establish an open access database holding experimental data on thermodynamic properties of CO₂ mixtures and data from corrosion tests of pipeline materials etc.</td>
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<tr>
<td>PR</td>
<td>Improve understanding of CO₂ transport leakage scenarios, with special emphasis on cost-efficient mitigation measures</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>PR</td>
<td>Assess and propose business models (led by economics research) for regional multi-user clusters of CO₂ sources. The chain-integration and build-out of the corresponding infrastructure should be studied (including connecting transport of CO₂ out from densely populated areas, cost-efficient CO₂ hubs, cross-border issues, operational issues of these complex systems and CCUS)</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>M</td>
<td>Efficient large-scale infrastructures for CO₂ (cost reduction aspects)</td>
<td></td>
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<tr>
<td>M</td>
<td>Cost-efficient and smart design of interim storage to respond to flexibility requirements</td>
<td></td>
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<tr>
<td>L</td>
<td>Meter technology and meter accuracy</td>
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</tbody>
</table>

Rankings: PR – Prioritised, M – Medium, L – Low  
Colour codes: Green – Validated, Yellow – Partly Validated, Red – Not Validated

#### 2.3.2 Storage drilling and subsurface facilities

Continued R&D can contribute significantly to further cost efficiency through innovative solutions and the overall learning curve of pilot (and demonstration) projects. Today, there is a high degree of uncertainty in estimating the costs for CO₂ storage projects because of significant variations between projects’ technical characteristics, scale and application.

There is also uncertainty as to how costs will develop over time with respect to the range of learning rates and scale benefits. The key challenge is to provide the basis for future cost reductions, taking into account location and type of storage site, reservoir capacity and quality. The UK Cost Reduction Task Force has recently concluded that early projects have high capital costs for several reasons, including:

- There are no commercial-scale projects to provide financiers with confidence.
- Storage risks are perceived as significant for early projects.
- Chain risks in the event that one component in the chain fails.

#### Key challenges and long-term R&D targets

- Build confidence in the operational performance of the CCS chain – particularly storage.
- Urgently establish up to six new CO₂ storage pilots EU-wide in order to accelerate state-of-the-art technology, drive down costs and increase public confidence in CO₂ storage.
<table>
<thead>
<tr>
<th>Rank</th>
<th>Key R&amp;D needs: storage drilling and subsurface facilities</th>
<th>-2020</th>
<th>2020-2030</th>
<th>2030+</th>
</tr>
</thead>
<tbody>
<tr>
<td>PR</td>
<td>Establish up to 6 new large CO₂ storage pilots, EU-wide: compared to the variety of potential geological settings for CO₂ storage, the number of operational onshore pilots is very low. With 3 operational pilots (Ketzin, Lacq and Hontomin), only limited research and operational knowledge is possible. The flexibility of such sites offers R&amp;D opportunities over the whole lifecycle of a storage project – from exploration to compliance, including closure and post-injection targets. The identification of research objectives should be based on previous Framework Programme research and national CCS R&amp;D programmes in, for example, Germany, France, The Netherlands, Norway, Spain and Denmark. The CO₂ for injection experiments must come from sources other than the commercial market, i.e. CO₂ streams that can be provided to and injected at the storage pilots need to be identified.</td>
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<tr>
<td>PR</td>
<td>Improve effective, low-cost monitoring systems</td>
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<tr>
<td>PR</td>
<td>Long-term monitoring (passive and active), plus cost-effective monitoring strategies</td>
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<tr>
<td>PR</td>
<td>Efficient 3D and 4D seismic onshore, including for use in permanent installations</td>
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<tr>
<td>PR</td>
<td>Improve drilling for cost-effectiveness and to reduce formation damage</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>Test cost-effective engineering solutions (compared to demonstration projects where off-the-shelf technologies would be expected). If planned ahead, parts of the high-capex surface facilities could potentially be shared between several pilot projects.</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>M</td>
<td>Wells and equipment: low-cost wells for exploration and observation, low-cost re-completion equipment (e.g. plastic liners) and durable long-life monitoring sonds</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>Quantify the effects of up-scaling on static and dynamic modelling on predictions of storage performance</td>
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</tbody>
</table>

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2.4 Accelerate state-of-the-art technology for transport and storage site operation

2.4.1 Contingency measures to reduce project risks

A CCS business case holds as long as all parts of the capture, transport and storage chain operate to design requirements at all times. The failure of any one part – while taking contingency measures into account – compromises the whole operation.

The FP7 RISCS project is one example of research where its “Guide to Impacts of Potential Leaks from CO₂ Storage” informs project developers on contingency measures that cannot be ‘appraised away’. It is particularly important that operational procedures for storage facilities and transport networks are developed and tested such that the CO₂ production facility has maximum availability.

Key challenges and long-term R&D targets
- Provide project developers with a suite of contingency measures that can used to assess technical business risks, i.e. research to concretise these risks, and plan for and cost the consequences of mitigation.
2.4.2 Processes for leakage scenarios

Research and experience provides indicative evidence that areas that might be affected by leakage from a storage complex would be small in size and limited to localised areas. Nevertheless, comprehensive knowledge of processes that would be active in different leakage scenarios is required (e.g. the consumption of CO₂ along leakage pathways). The licence holder of a storage site needs guidance as to whether a detected leakage will lead to binary consequences for the operation, i.e. a complete stop of operation, or given that the environmental impact is low, that operation can continue with restrictions.

Key challenges and long-term R&D targets
- Provide comprehensive knowledge on processes that would be active in different leakage scenarios.

2.4.3 Dynamics, monitoring and remediation

There are additional operational challenges to those covered in sections 2.4.1 and 2.4.2. To a large extent, these would have been addressed in the discontinued demonstration projects, including the effects of transient operational scenarios imposed by the CO₂ capturing plant in the flow line and wells, and monitoring and remediation technologies.

Key challenges and long-term R&D targets
- Flexible injection schemes without harming the well-bore (micro seismicity, thermal cycling well-bore, thermal wave-chocks)
- Technologies for remediation and mitigation of significant irregularities and leakage
- Extended offshore baseline data.

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### Key R&D needs: contingency measures for CO₂ storage and transport

<table>
<thead>
<tr>
<th>Rank</th>
<th>Key R&amp;D needs</th>
<th>-2020</th>
<th>2020-2030</th>
<th>2030+</th>
</tr>
</thead>
<tbody>
<tr>
<td>PR</td>
<td>When storage capacity is lower than assessed: requires pressure management, especially for deep saline aquifers, to maximise the storage resource and monitor the effects of pressure build-up. Understand pressure responses and pressure management techniques (e.g. by water extraction).</td>
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<tr>
<td>PR</td>
<td>When the plume does not behave as expected: requires spatial development of the CO₂ plume (steering, control mechanisms, saturation distribution, re-production of CO₂). Assess economic and technical cut-off for extraction of water in order to make more efficient use of the pore space (including disposal and re-use opportunities).</td>
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<tr>
<td>PR</td>
<td>When there is poor sustained injectivity: requires research on the consequences of the migration of fines, geochemical impacts</td>
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<tr>
<td>PR</td>
<td>Re. transport modes: extraordinary transport operational procedures are required in case of upstream and/or downstream disturbances</td>
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</tbody>
</table>

Rankings: PR – Prioritised, M – Medium, L – Low
Colour codes: Green – Validated, Yellow – Partly Validated, Red – Not Validated

### Key R&D needs: potential migration pathways and environmental impacts of CO₂ leakage

<table>
<thead>
<tr>
<th>Rank</th>
<th>Key R&amp;D needs</th>
<th>-2020</th>
<th>2020-2030</th>
<th>2030+</th>
</tr>
</thead>
<tbody>
<tr>
<td>PR</td>
<td>Improved prediction (based on controlled release experiments) of geologically-controlled CO₂ leakage mechanisms (rate, timing, consequences, probability). Consumption of CO₂ along leakage pathways.</td>
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<tr>
<td>M</td>
<td>Gain further experience on the impact of leaked CO₂ on crops etc., as currently being undertaken in the FP7 RISCS project.</td>
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</table>

Rankings: PR – Prioritised, M – Medium, L – Low
Colour codes: Green – Validated, Yellow – Partly Validated, Red – Not Validated
<table>
<thead>
<tr>
<th>Rank</th>
<th>Key R&amp;D needs: dynamics, monitoring and remediation</th>
<th>-2020</th>
<th>2020-2030</th>
<th>2030+</th>
</tr>
</thead>
<tbody>
<tr>
<td>PR</td>
<td>Assessment of the impact from micro-seismicity, thermal cycling and thermal waveform on the well-bore and its installation from flexible injection schemes</td>
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<tr>
<td>PR</td>
<td>Technologies for remediation and mitigation of significant irregularities and leakage</td>
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<tr>
<td>PR</td>
<td>Remediation testing facility: field-scale tests are needed to demonstrate the effectiveness of technologies for controlling permeability, implementing hydraulic barriers and fluid management to remediate geologically-mediated migration for CO$_2$ storage applications</td>
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<tr>
<td>PR</td>
<td>Extended gathering of offshore baseline data, building on the FP7 ECO2 project (e.g. in the Baltic Sea)</td>
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<tr>
<td>M</td>
<td>Remote sensing (InSAR, EM etc.) for leakage detection and geomechanical stability; plus cost reduction opportunities</td>
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<td></td>
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<tr>
<td>M</td>
<td>Biological monitoring for environmental impact</td>
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<tr>
<td>M</td>
<td>Reservoir and over seal monitoring (resolution/sensitivity) – Time lapse seismic techniques for increased resolution – Micro-seismic design – Monitoring bore design and down-hole sensors</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>Well closure and abandonment procedures</td>
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<tr>
<td>L</td>
<td>Automated statistical procedures to define deviation thresholds in monitoring data sets compared to baseline (data mining)</td>
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</tbody>
</table>

Rankings: PR – Prioritised, M – Medium, L – Low  
Colour codes: Green – Validated, Yellow – Partly Validated, Red – Not Validated

### 2.5 Establish clear post-injection procedures

Projects require certainty as to the degree of monitoring and activity required in the period covering post-closure stewardship. Post-injection monitoring is essential to verify expectations regarding long-term stability and storage permanence. The results of that monitoring determine when the site is returned to the public authorities.

Developers of commercial projects therefore need clarity regarding procedures and criteria in the early phase of project development in order to evaluate how and when targets can be met to reduce overall project risks. This also facilitates the setting of storage tariffs. The key challenge is to understand the processes taking place which lead to stability and a reduction in risk.

**Key challenges and long-term R&D targets**
- Develop key performance criteria for the guidance of project developers, regulators and policymakers.

### 2.6 Reduce uncertainty for site operators regarding liability

Research to date points to two sources of uncertainty with regard to handling liability: performance of the physical system itself and policy measures to handle liability. The latter is linked to the risks of the former, i.e. uncertainty over the long-term performance of storage sites needs to be reduced so that the liability provision of policy measures can be better judged by project developers.
Research is needed on the likelihood of irregularities occurring and their consequences. Further evidence is needed that irregularities — if they occur — do not have detrimental consequences for a storage project, thereby de-risking projects. Indeed, the more work undertaken on the potential consequences, the better informed the debate surrounding HSE issues.

**Key challenges and long-term R&D targets**
- Reduce uncertainty over the long-term performance of CO₂ storage sites, guiding informed liability policy measures.

<table>
<thead>
<tr>
<th>Rank</th>
<th>Key R&amp;D needs: liability</th>
<th>-2020</th>
<th>2020-2030</th>
<th>2030+</th>
</tr>
</thead>
<tbody>
<tr>
<td>PR</td>
<td>CO₂ plume tracking, leakage detection and quantification of leakage at surface (especially offshore)</td>
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<tr>
<td>PR</td>
<td>Pressure propagation into potable aquifers</td>
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<tr>
<td>M</td>
<td>The fate of the CO₂: dissolution, residual trapping and associated time-scales, processes at pore-scale, residual saturation of CO₂ in the pore network, saturation fronts, processes at grain surfaces, impact of wettability and subsequent change. Validating predictions of CO₂-fluid reactions against data obtained at scale in realistic injection and storage scenarios.</td>
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<tr>
<td>M</td>
<td>Longer-term trapping: natural CO₂ reservoirs can be used to evaluate the potential for these processes to contribute to long-term site safety cases by constraining predictions of site behaviour with analogue data. Provide reference data sets from natural reservoirs which have been produced for benchmarking predictive simulations and newly acquired monitoring data.</td>
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<tr>
<td>M</td>
<td>Ecosystem recovery</td>
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<tr>
<td>M</td>
<td>Well integrity and flow monitoring facility: gain experience of the long-term stability of well completion materials</td>
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</tbody>
</table>

Rankings: PR – Prioritised, M – Medium, L – Low
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### 2.7 Maximise the benefits of CCU/CCUS as an enabling technology for CCS

There is a range of CO₂ storage options available. A key challenge is therefore to further assess options that – in addition to deep saline aquifers and depleted oil/gas fields – have attractive benefits from an industrial perspective, e.g. the use of CO₂ to enhance recovery efficiency in oil fields, combining aquifer storage with geothermal energy.

**Key challenges and long-term R&D targets**
- Further assess options that have attractive industrial and societal benefits.

<table>
<thead>
<tr>
<th>Rank</th>
<th>Key R&amp;D needs: additional CO₂ storage concepts</th>
<th>-2020</th>
<th>2020-2030</th>
<th>2030+</th>
</tr>
</thead>
<tbody>
<tr>
<td>PR</td>
<td>Co-optimisation of CO₂ storage and EOR</td>
<td></td>
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<tr>
<td>M</td>
<td>Combine CO₂ storage and geothermal heat extraction (water production to control pressure build-up)</td>
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<tr>
<td>M</td>
<td>Reproduction of part of the stored CO₂ for CCUS</td>
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</tbody>
</table>

Rankings: PR – Prioritised, M – Medium, L – Low
Colour codes: Green – Validated, Yellow – Partly Validated, Red – Not Validated