D1.5 Updated ECCSEL Research Priorities

Robert de Kler, Sigurd Løvseth, Galina Skorikova, Helen Taylor-Curran, Ceri Vincent

Lead participant: UKRI-BGS

Dissemination level: Public

RIA Research and Innovation Action project Grant Agreement (GA) No. 871143

Type of funding scheme

RIA Research and Innovation action: Development and long-term sustainability of new pan-European research infrastructures

Work programme topics addressed

INFRADEV-03-2018-2020 - Individual support to ESFRI and other world-class research infrastructures

Start date of project: 01 January 2020
Duration: 3 years

Deliverable number:	D1.5
Deliverable name:	Updated ECCSEL ERIC Research Priorities
Work package:	WP1 ECCSEL ERIC research strategy and services model development
Lead participant:	UKRI

Dissemination Level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

Author(s)	
Name	**Organisation**
Robert de Kler	TNO
Galina Skorikova	TNO
Helen Taylor-Curran	UKRI-BGS

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Ceri Vincent	UKRI-BGS
Sigurd Løvseth	SINTEF

Abstract

This ECCSELERATE project deliverable D1.5 is the refreshed ECCSEL Research Priorities and the first formal update of ECCSEL's research priorities since the ECCSEL Research Strategy Roadmap was issued in 2017.

The aim of this report is to enable ECCSEL to make strategic decisions to support infrastructure development such as:

- upgrades and new facilities identified in the Infrastructure Development Plan (WP2)
- high priority, high value, and large-scale research facilities (for example the exercise underway in ECCSELERATE WP2), and
- determining the scope of calls for transnational access proposals (e.g. ECCSELERATE WP3 and WP8).

This report updates research priorities for CO_2 transport and storage, sets detailed research priorities for CO_2 capture, and for the first time identifies priorities and high-level requirements for research facilities in CO_2 utilisation. The report also incorporates the outcomes from dedicated industrial sector workshops that sought feedback on their priorities for research, and on services that ECCSEL ERIC could usefully offer to industry.

History of document

First draft completed	First draft completed 4 August 2022 and sent to WP1 for revision
WP1 revision (v0.5) completed and sent to PMG for approval	29 September 2022
Document (v1.0) completed	21 October 2022

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Executive Summary

Context for the ECCSEL research priority summaries

ECCSEL ERIC ('ECCSEL') is the European research infrastructure (RI) for carbon dioxide capture, utilisation and storage (CCUS), an important emissions reduction technology that can be applied across industry covering the entire energy system. ECCSEL's research priorities are developed as a continuous, iterative process. They aim to take account of:

- the evolution of ECCSEL and its facilities
- ECCSEL's Infrastructure Development Plan (Ræder and ECCSEL ERIC, 2022), which sets out planned facility upgrades and construction, and identifies remaining gaps according to anticipated research directions
- viewpoints shared during dedicated ECCSEL industry stakeholder workshops and interactions with other stakeholder groups
- the broader European CCUS research and infrastructure landscape as we understand it.

ECCSEL's research priorities are summarised in the tables that follow:

Table 1: CO_2 Capture - Research priorities and infrastructure needs
Table 2: CO_2 Capture - High level research and infrastructure needs and potential services for industry
Table 3: CO_2 Utilisation - Research priorities and infrastructure needs
Table 4: CO_2 Utilisation - High level research and infrastructure needs for industry
Table 5: CO_2 Transport and Fluid Properties - Research priorities and infrastructure needs
Table 6: CO_2 Storage - Research priorities and infrastructure needs

Supporting narratives and rationale can be found in the four chapters that deal separately with each element of the CCUS value chain, forming the main body of this report, i.e.

- CO_2 Capture - Research Priorities and Infrastructure Needs
- CO_2 Utilisation - Research Priorities and Infrastructure Needs

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- CO_2 Transport and Fluid Properties - Research Priorities and Infrastructure Needs
- CO_2 Storage - Research Priorities and Infrastructure Needs

The priority level indicated for each item (in the summary table, and in the supporting narrative) reflects ECCSEL's view of the importance of addressing the research need to overcome barriers to broad CCUS deployment in Europe; it does not refer to the facility requirements identified. Finally, while the ECCSEL research priorities have been discussed and refined extensively with stakeholders over the five years since their original publication in 2017, these indicative priority levels, as well as the research priorities and emerging facility needs, reflect the views of the authors.

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Table 1: CO_2 Capture - Research priorities and infrastructure needs

*priority level of the research, not the facility, preliminary ranking by ECCSEL (see text)

Priority*	Key aim of research	Specific research questions	CO_2 capture research facilities required
HIGH	Liquid absorbents: Understanding the structure, properties and physical processes of absorbents, new supporting computational modelling methods	The physical processes of absorption in the absorbent and at the interface level must be understood and modelled in detail. Absorbents must be characterised in a working state, at different levels of resolutions, subject to the separation process and its process integration.	To follow
		Understanding the governing relationships between chemical and physical absorbents structure and properties and the transfer of know-how in conceptual design and new solvents.	
		Tool kit of approaches to liquid absorption separation expanded to encompass new materials and new physical and chemical switches that go beyond traditional thermal and pressure swings.	
		New computational methods for new absorbents and to understand the capture process at all levels of detail to enable the design of the liquid absorption process to be fundamentally underpinned.	
HIGH	Solid sorbents: Development of novel highly selective new materials and triggers, new supporting computational modelling methods	Development of new materials with novel architectures and functionalities to selectively uptake and release CO_2, to allow for a more thermoneutral sorption (uptake and release) process.	To follow
		Understanding the key structural features of selective sorption of CO_2.	
		Intensification of the process by combining capture and reaction (direct utilisation or water-gas-shift reaction).	
		Development of new techniques that allow in-situ monitoring of gas sorption and online analysis of structural transformation of sorbent material.	

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Priority*	Key aim of research	Specific research questions	CO_2 capture research facilities required
		Identification of new triggers for selective capture and release, so-called smart materials.	
		Computational methods to characterise structure-properties relationships for (new) solid sorbents.	
HIGH	Membrane systems: Fundamental research to understand membrane transport at the atomic and molecular level, new computational design methods	Understanding the atomic- and molecular-level processes that affect separation performance in membranes, including mechanisms of neutral, ion, and electron transport through a membrane.	To follow
		Computational methods to design and to optimise the separation of hierarchical structures, hybrid organic/inorganic structures, tailored functionalities, catalysts, and other features to enhance transport and selectivity, and improve stability.	
HIGH	Membrane systems: Development of novel triggers and new membrane systems including smart/self-assembling/self-repairing systems with low energy cost	New approaches for membrane separation and alternative driving forces or specific membrane-permeate interactions that can enable separations that are less energy-intensive than conventional temperature and pressure swings.	To follow
		New concepts for the design of membrane separation systems, incorporating self-assembly and even self-repairing strategies, and/or multifunctional structures. New concepts that could incorporate hybrid or "smart" materials that alter the transport of a targeted gas or ion on application of a specific external trigger.	

Table 2: CO_2 Capture - High level research and infrastructure needs and potential services for industry

*priority level of the research topic, not the facility, preliminary ranking by ECCSEL (see text); †current TRL

Priority*	Key aim of research	Specific research questions	TRL†	Industrial sectors	CO_2 capture research facilities required	Services
HIGH	Chemical post combustion capture	Improve solvent lifetime Lower energy needs	7	Waste, cement, steel, petrochemical	Mobile units for on-site testing and training of technicians in operation, solvent management etc	Capacity building, knowledge sharing
HIGH	Hydrogen firing (high temperature heating	NO_x emission Operational flexibility/hybrid	6	Steel, petrochemical	Burner test facility	Joint research, capacity building, knowledge sharing
HIGH	Calcium looping	Sorbent durability	7	Cement	Research demonstration plant	Joint research
MEDIUM	Oxy fuel combustion	Upscaling	6	Cement	Research demonstration plant	Joint research, knowledge sharing
HIGH	Pre-combustion adsorption	Sorbent durability Sorbent lifetime Upscaling	6	Steel	Large scale demonstration plant	Joint research
HIGH	Post combustion membrane capture	Show durability Upscaling Energy numbers at pilot-scale Feasibility of CO_2 purity and recovery	6-7	Cement, lime, refinery, maritime	Large scale mobile demonstration plant	Joint research, capacity building, knowledge sharing

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Table 3: CO_2 Utilisation - Research priorities and infrastructure needs

*priority level of the research topic, not the facility, preliminary ranking by ECCSEL (see text)

Priority*	Key priority aim	Specific research questions	CO_2 utilisation research facilities required
HIGH	Mineralisation/carbonation	Assess and improve mineralisation technologies Improve technologies that directly process flue gas, avoiding the need for purified CO_2	Research pilots capable of simultaneously testing multiple physical and chemical processes under realistic conditions
HIGH	CCU fuels, polymers and other chemicals	Identify catalysts with high efficiency, stability, and reliability Convert CO_2-fuels through gas fermentation Address challenges like low CO_2 solubility in water	Research pilots capable of simultaneously testing multiple physical and chemical processes under realistic conditions

Table 4: CO_2 Utilisation - High level research and infrastructure needs for industry

*priority level of the research topic, not the facility, preliminary ranking by ECCSEL (see text)

Priority*	Key priority aim	Specific research questions	CO_2 utilisation research facilities required
LOW	Delivery to greenhouses	n/a	n/a
MEDIUM	Methanol production	Production rate Upscaling	To follow
HIGH	Direct conversion on site to valuable products	Development of sustainable production routes	To follow
HIGH	Integration of capture technologies and downstream recovery technologies into fuels or other functional platform molecules	Development of new circular value chains and sustainable production routes based integrated system from point sources and Direct Air Capture technologies	To follow

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Table 5: CO_2 Transport and Fluid Properties - Research priorities and infrastructure needs

*priority level of the research topic, not the facility, preliminary ranking by ECCSEL (see text)

Priority*	Key aim of research	Specific research questions	CO_2 transport research facilities required
HIGH	Properties of CO_2 and CO_2 mixtures	Quantifying knowledge gaps in properties most important for the design and operations of CCS processes and systems, and to which model predictions are the most sensitive i.e. • Phase equilibria, including high pressure, reactive components and solids (dry ice, ice, hydrates, salts, etc) • Density • Heat capacity/caloric properties • Speed of sound • Thermal conductivity • Interfacial tension • Viscosity • Diffusion coefficient	Thermophysical properties facilities for CO_2/CO_2 rich mixtures and trace components in CCS relevant conditions covering phase equilibria, density, flow calorimetry, speed of sound, interfacial tension, thermal conductivity and diffusivity
HIGH	Flow characterisation in pipelines and wells, ship transport	Detailed characterisation of CO_2 flow • Pressure drop • Gas/liquid volume fractions • Temperature • Mass flow rate • Transient analysis for control and operation of networks handling CO_2 from multiple sources • Characterisation of flow downstream of depressurisation especially understanding formation of solids and related kinetics • Clogging of safety equipment • Loading of low-pressure CO_2-transport ships. • Transient vertical flow in wells (for start-up, shut-in, re-pressurisation, depressurisation, blow-out, unloading of ships etc). • Batch vs continuous unloading, buffering systems, flexible hoses for offshore unloading of ships	Facility to investigate transient phenomena related to CO_2 transport – FASafe now in construction via ECCSEL NFS Flow assurance in safety systems Valve flow characterisation facility
HIGH	Fiscal metering and flow monitoring	Accurate fiscal metering solutions for CO_2, including: • Verification of flow meter technologies, further development of flow meters if is found that current state of the art is not sufficient. • Procedures and infrastructure to ensure traceability within the ETS requirements • Investigation of impact of transients and impurities	Large scale test facility for fiscal metering of CO_2 and CO_2 mixtures

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Priority*	Key aim of research	Specific research questions	CO_2 transport research facilities required
		• Development of systems for monitoring and control of complex CO_2 transport systems serving industrial sources • Adaption of flow simulation tools for CO_2 transport linked to online sensors • Advancement of thermodynamic and flow models necessitating new thermodynamic fluid • Development and verification of online sensing technologies regarding e.g. onset of minor second phase, composition of relevant chemical systems and flow rates	Test facility for flow monitoring instrumentation
MEDIUM	Pipeline and tank integrity	Running-ductile fracture data for development and validation of models Flow from cracks/along flaps in pipes Thermophysical properties (above)	Facility for characterisation of pressure along pipe flaps Accurate facility for investigation of corrosion
HIGH	Non-equilibrium phenomena	Non-equilibrium studies to evaluate potential for BLEVE Kinetics of solid CO_2 formation/melting/sublimation (above)	Facility for BLEVE wave structures, kinetics of solid formation, sublimation, melting (FASafe?)
MEDIUM	Compatibility of non-metallic components in CO_2 value chain	Understanding stability and performance of non-metallic polymer components exposed to CO_2 or CO_2 mixtures: • Molecular structure and CO_2 solubility in polymers • Impact of CO_2 impurities on polymer components • Extraction of low MW components from the polymer phase, changing the physical and chemical properties of the polymer (elastomers) • Effect of rapid gas decompression (RGD) on integrity of non-metallic exposed to CO_2 and stability towards dynamic loadings (elastomers/thermoplastics) • Effect of CO_2 on polymer coatings for metal pipelines (swelling, delamination, possible debris detachment) Barrier performance and suitability of existing risers used in flexible pipes when in contact with dense phase CO_2.	Facility for exposure and RGD of polymer to CO_2 up to 300 bar (measurement of swelling and physical integrity). Test rig for determination of CO_2 solubility in polymers for dense phase and liquid CO_2. Model for prediction of polymer/CO_2 compatibility under relevant operating conditions

Table 6: CO_2 Storage - Research priorities and infrastructure needs

*priority level of the research topic, not the facility, preliminary ranking by ECCSEL (see text)

Priority*	Key aim of research	Specific research questions	CO_2 storage research facilities required
HIGH	Dynamic storage capacity and understanding the pressure-connected volume	Improving predictions of dynamic properties with real thermophysical property data Improved techniques for integrated modelling (geochemical, geomechanical and flow modelling with multiple fluids and phases, relative permeabilities for target formations) Understanding and modelling the pressure footprint/gradients, and satisfying regulatory requirements to show site is behaving as expected, including when preparing for site closure Model iteration; assessing how much models change as more data become available during operation Pressure management through water production to increase available storage capacity Practical evidence of impacts of heterogeneities through experiments at pilots Pressure implications of multiple injections in connected formations from multiple storage operations Optimise integration of high-resolution models into regional models for regional processes and improved representation of heterogeneities	Model/monitoring loop and site assurance (improved integrated modelling, real thermophysical data) Pressure pilot: Saline aquifer and interactions between multiple injections Injection pilot: Compartmentalised/ heterogeneous saline aquifer
HIGH	Storage optimisation through development of a range of injection strategies	How to test representative pore volumes for many km^2 and long periods (more than a few hours) from weeks to months How to predict the size of the pressure-connected volume that is in reach of one well, especially in saline aquifers Innovation around injection for enhancing storage injection rates and capacity, e.g. impacts of discontinuous injection on storage efficiency and trapping mechanisms Understanding and monitoring CO_2 behaviour in the well and near-well environment (phase changes, hydrates, impacts of heterogeneities and trace components in the CO_2 stream)	Laboratory: Multiphase flow, real thermophysical data Pilot: Enhancing storage injection rates and capacity, predicting and modelling pressure-connected volume in saline aquifers Testbed: well issues and CO_2 behaviour
MEDIUM-HIGH	Site selection and demonstrating security of storage	Demonstrating the minimum data needed to assure storage capacity and to meet regulatory/permitting requirements	Testbed or pilot: Fault permeability, aquifer

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Priority*	Key aim of research	Specific research questions	CO_2 storage research facilities required
		Factors that impact over- and under-burden integrity e.g. fatigue when re-using depleted hydrocarbon fields, fracture-controlled migration in low permeability materials Fault behaviour: • What data are essential in predicting fault behaviour? • Pilot-scale tests to validate predictive capability • Improved microseismic data collection techniques and integration into models • Fault detection (in caprocks) e.g. via high-resolution seismics and image logging Interactions with other (sub)surface actors for the transition to net zero (e.g. hydrogen, geothermal, wind farms, green industrial revolution)	Testbed: Long term fault permeability Testbed: Failure of reservoir and caprock or underburden integrity Testbed: Low integrity caprock
MEDIUM-HIGH	Monitoring for assurance and long-term containment	More efficient cost-effective monitoring techniques to demonstrate reservoir behaviour and satisfy regulatory requirements, including during the closure and post-closure stages High-resolution permanent/continuous and sparse MMVQ techniques (e.g. improved repeatability, improved temporal and spatial resolution at lower costs and spatial scaling) Non-invasive monitoring of the storage complex with minimal wells/interruption of the seal Monitoring with minimal operational demands/low maintenance (e.g., automated alerts, remote monitoring techniques) Quantification of CO_2 in the subsurface for site assurance	Permanent/continuous monitoring, non-invasive techniques, low maintenance/operational demand Data management - real-time data management, automatic alerts, machine learning for data processing and interpretation
MEDIUM		Leakage detection and quantification (e.g. with UAVs or continuous monitoring stations) Detection of unwanted migration of CO_2 towards leakage pathways/in leakage pathways or other unexpected events that would trigger contingency monitoring Well completion (e.g. long term monitoring technologies, long term stability of well materials)	Developing tools for leakage detection and measurement – on/offshore testbed, multi-sensor platforms Laboratory: wellbore material reactions Field laboratory: wellbore completion
MEDIUM-HIGH	Developing remediation and mitigation techniques	New subsurface in-reservoir and in-overburden mitigation and remediation technologies, including managing well issues Remediation and mitigation at depth, including plume steering and reproduction of CO_2 to reduce pressure Chemical/biological techniques specific to CO_2 storage Practical experience in remediation	Testbed – practical testing of remediation techniques

Priority*	Key aim of research	Specific research questions	CO_2 storage research facilities required
HIGH	Storage permitting	Pilot scale storage project to ‘dry run’/ inform discussions Liability and risk management Demonstrating that the site is ready for handover and post-injection management	Pilot (project): moderate quantity of stored CO_2

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Introduction

ECCSEL ERIC and the ECCSELERATE project

ECCSEL ERIC ('ECCSEL') is the European research infrastructure (RI) for carbon dioxide capture, utilisation and storage (CCUS), an important emissions reduction technology that can be applied across industry covering the entire energy system. ECCSEL was established with funding from the European Union's FP7 and Horizon 2020 research and innovation programmes under Grant Agreements 262512, 312806 and 675206. The legal entity ECCSEL ERIC (European Research Infrastructure Consortium) was implemented under Commission Implementing Regulation (EU) 2017/988 on 6 June 2017. ECCSEL is a unique instrument for the effective use of research facilities to accelerate technology development for carbon capture, utilisation, transport and storage. ECCSEL provides access to over 100 research facilities specialising in CO_2 capture, transport, storage and, more recently, utilisation, from across its member countries, and coordinates the development of CCUS research infrastructure and services to meet European CCUS deployment research needs.

This report is a formal deliverable of the European Commission Horizon 2020 ECCSELERATE project, a three-year project funded under Research and Innovation Action project Grant Agreement 871143. Two key objectives of the ECCSELERATE project are to increase user access and ensure the long-term sustainability of the ECCSEL RI, as it transitions from its early operational phase as an ERIC, to an advanced stage of operation.

Background to the ECCSEL research priorities

The ECCSEL Research Strategy Roadmap (the 'Roadmap', Pearce et al., 2017) was a deliverable of the Horizon 2020 ECCSEL Implementation Phase project (EC Grant Agreement 675206). The Roadmap was co-developed by the project consortium members and represents their views of their national and research community priorities and perspectives. Research priorities for CO_2 transport and storage were relatively well understood from a range of aligned activities e.g. EERA CCS Joint Programme, Mission Innovation, industry bodies (e.g. CSLF) and the research community (e.g. EGS, CO2GeoNet, national Club CO_2s and CCS research coordination groups and institutes). This allowed ECCSEL to be quite specific in identifying research needs, and even taking this as

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far as identifying gaps in research infrastructure for CO_2 transport and storage aspects of the CCS value chain.

Specific research needs in CO_2 capture were more difficult to define at that point. Capture research priorities had been considered from the perspective of power generation, differentiated into post- and pre-combustion, and oxy-fuel approaches. Gaining a consensus on research topics that ECCSEL should focus on was challenging, let alone identifying infrastructure gaps and research facilities that might be required. The Roadmap development coincided with the general widening of CCUS application from power generation towards CO_2- and energy-intensive industries that are difficult to decarbonise, forcing a shift in thinking from power generation processes to the separation technologies involved in CO_2 capture. Without a dedicated programme of consultations directly with these industries, ECCSEL was not able to develop CO_2 capture research priorities much further than setting out very high-level research needs and identifying next steps at the time.

In 2017, utilisation (use) of captured CO_2 (CCUS) was beyond the scope of ECCSEL and the Roadmap but was becoming increasingly important to national efforts to implement CCS among ECCSEL's existing and potential new members. ECCSEL's policy on the inclusion of CO_2 use technologies (in research priorities and in facilities) was agreed by its members in 2018, and can be summarised as 'permanence of storage' i.e. that, in order to align with ECCSEL's mission to enable net zero power generation and industry, CO_2 use technologies falling within the scope would result in carbon removal on a long-term, ideally near-permanent basis, directly contributing to climate change mitigation efforts. ECCSEL has since carried out detailed work to understand which technologies would fall within ECCSEL scope (Chavez and Shinde, 2021; Jansen et al., 2022a) and are included in this research priorities update.

The outcomes of the Roadmap have been disseminated and discussed with CCS community stakeholders at national, European and international level since their publication. As a result, the updated research priorities for CO_2 transport and storage needed refreshing for advances through recent research, but are still broadly in line with the original Roadmap, although the infrastructure required to address these priorities has shifted slightly, reflecting investments in CCS research facilities across the ECCSEL members and Europe more generally. From ECCSEL's consultations with industry (Jansen et al., 2022a, b), and with its growing community of facility owners during the update of the ECCSEL Infrastructure Development Plan (Ræder and ECCSEL ERIC, 2022), we are now also able to provide a clearer picture of the research priorities and infrastructure requirements for CO_2 capture and utilisation.

Purpose, scope and structure of the report

The purpose of this report is to refresh the 2017 ECCSEL Research Strategy Roadmap (Pearce et al., 2017), focussing on the research needs and resulting infrastructure requirements across the CCUS value chain, to enable ECCSEL to make strategic decisions to support research infrastructure development e.g.

- upgrades and new facilities identified in the updated Infrastructure Development Plan (Ræder and ECCSEL ERIC, 2022)
- construction of high priority, high value, large-scale research facility (e.g. the exercise underway in ECCSELERATE WP2), and
- defining the scope of transnational access calls (e.g. work underway in ECCSELERATE WP3 and WP8, https://www.eccsel.org/abouteu-grants/eccselerate/).

This report updates ECCSEL's research priorities for CO_2 transport and storage, and now also sets out more detailed research priorities for CO_2 capture as well as CO_2 utilisation than had been possible previously. The report includes, and is informed by, the high-level outcomes from industrial workshops and interviews on sector-specific research priorities, as well as services that ECCSEL could usefully provide to industry (Jansen et al., 2022a).

Research priorities for CO_2 capture, CO_2 use, CO_2 transport and CO_2 storage are summarised in a series of tables in the Executive Summary. The narratives and rationale that underpin these priorities are set out in four sections making up the body of this report, each dedicated to a specific element of the CCUS value chain. ECCSEL also assigns a level of priority to research needs, based on the expected impact on overcoming research barriers to broad deployment of CCUS. Alongside the national perspectives and priorities on implementation of CCUS, this prioritisation helps steer ECCSEL towards the key research infrastructure that the RI could usefully develop in future. While this prioritisation has proved uncontroversial throughout dissemination and discussion with a range of CCS community stakeholders so far, it nonetheless reflects the views of the ECCSEL authors.

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CO_2 Capture - Research Priorities and Infrastructure Needs

Of the two CO_2 removal methods deemed to be key industrial technology directions for the energy transition, the focus of energy (and CO_2) intensive industry is mainly on point source CO_2 capture where there is a pressing need for practical and cost-effective methods to capture CO_2. So far, CO_2 capture technologies are expensive, large, energy intensive, and require complex implementation. The second method is direct air capture, an emerging development driven mainly by SMEs with fast-growing industrial engagement. Both removal methods have gained significant policy and legislative support in the EU; reference is made to the innovation fund program in the EU portal, where a list of DAC projects are listed. It is imperative for both methods that the thermodynamically stable CO_2 molecule is captured rapidly and selectively and with relatively little energy input.

Defining the research needs for carbon capture technologies is a complex task. For ECCSEL, capture research needs have conventionally been considered in terms of pre-combustion, post-combustion and oxy-fuel combustion, as drawn from the power generation sector. This approach does not lead to a straightforward prioritisation of CO_2 capture research needs, or a strategic focus for ECCSEL in developing capture research facilities. It takes insufficient account of plant-specific issues in implementing CO_2 capture in power generation (a traditional focus of ECCSEL), and it places too little emphasis energy-intensive industry scenarios with their own pressing needs to reduce emissions.

Here we approach the research needs for CO_2 capture by separation technology, based on industrial R&D. There are three main streams in separation technologies for different CO_2 capture applications - liquid absorption, solid sorbents, and membranes - the following key research needs are identified and are explained along these technology streams; research needs are also summarised in the Executive Summary, Table 1.

Industrial research priorities have been exhaustively discussed during a series of dedicated workshops (Jansen et al., 2022a). Most of the participants provided details about ongoing research activities and pilot plant projects for CCUS. In the Executive Summary,

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Table 2 summarises research priorities and research facilities, that ECCSEL could help with getting in place.

The industrial challenges that sit alongside the case-specific scientific challenges in

Table 2 will require significant advances in characterisation tools and research infrastructure that can simultaneously monitor multiple physical and chemical processes under realistic conditions. As a result, the research needs that follow are considered high priority, since it is crucial they are addressed for the further development of capture technologies. Results will be used for designing materials, structures, and driving forces that will be incorporated in a new generation of separation processes for reducing CO_2 emissions.

Technologies based on oxy-fuel combustion are of interest in industries where the production of CO_2 is unavoidable, such as cement production. Here oxy-fuel operation is an option for direct production of pure CO_2. The current industrial research focuses on retrofitting a plant to prove the concept on large scale.

In addition to the different priorities for CO_2 capture in the industries consulted, high importance was placed on operating their processes with electricity or hydrogen to avoid producing CO_2 themselves. As such industries require changes to their equipment to handle hydrogen in their burners for indirect and direct heating, burner test facilities are needed to conduct the testing.

Liquid absorption

Of the available CO_2 capture technologies, chemical post-combustion is among the most proven. Many industrial sectors are actively exploring the potential application, selection and further development of liquid

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sorbents to improve longevity, energy requirements and performance, as well as their application to different flue gas compositions and purity requirements. Liquid absorption can potentially be applied in all industrial sectors and is already applied at large industrial scales ranging from TRL7 to TRL9. There is an urgent need for further improvement; liquid absorption research needs are focussed on better understanding the structure, properties and physical processes of absorbents, as well as improving process conditions and system integration including computational modelling methods:

- The physical processes of absorption in the absorbent and at the interface level must be understood and modelled in detail. Absorbents must be characterised in a working state, at different levels of resolutions, subject to the separation process and its process integration.
- Understanding the governing relationships between chemical and physical absorbents' structure and properties and the transfer of know-how in conceptual design and new solvents.
- Tool kit of approaches to liquid absorption separation expanded to encompass new materials and new physical and chemical switches that go beyond traditional thermal and pressure swings.
- New computational methods for new absorbents and to understand the capture process at all levels of detail to enable the design of the liquid absorption process to be fundamentally underpinned.

Priority: High

Facilities required:

- **Mobile units: on-site testing and training of technicians in operation, solvent management etc ≥TRL7**
- **Burner test facility: pre-combustion for hydrogen firing ≥TRL6**

Services:

- **Joint research**
- **Capacity building**
- **Knowledge sharing**

Industry sectors:

- **Energy from Waste**
- **Cement**

- **Steel**
- **Petrochemical**

Solid adsorbents

Capture technologies based on solid adsorption, such as calcium looping, and sorption-enhanced water gas shift are of specific interest in their respective industries e.g. cement and steel. For both, development focus lies in proving the process at scale and over long periods to study sorbent behaviour, durability and performance. Large scale demonstration plants are needed to conduct this research. Test facilities are also needed to screen gas compositions of other industries to assess the potential to apply these technologies more broadly. Currently, pilot applications using solid adsorbents can be found in the steel and cement industries at TRL6 to TRL7. Solid adsorbent research requires the development of novel, highly selective new materials and triggers, and supporting computational modelling methods:

- Development of new materials with novel architectures and functionalities to selectively uptake and release CO_2, to allow for a more thermoneutral sorption (uptake and release) process
- Understanding the key structural features of selective sorption of CO_2
- Intensification of the process by combining capture and reaction (direct utilisation or water-gas-shift reaction)
- Computational methods to characterise structure-properties relationships for (new) solid sorbents
- Development of new techniques that allow in-situ monitoring of gas sorption and online analysis of structural transformation of sorbent material
- Identification of new triggers for selective capture and release, so-called smart materials

Priority: High

Facilities required:

- **Research demonstration plant: calcium looping ≥TRL7**
- **Large scale demonstration plant: pre-combustion adsorption ≥TRL6**

Services:

- **Joint research**

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Sectors:

- **Cement**
- **Steel**

Priority: Medium

Facilities required:

- **Research demonstration plant: oxy-fuel combustion ≥TRL6**

Services:

- **Joint research**
- **Knowledge sharing**

Sectors:

- **Cement**

Membranes

Membranes may have a large potential for application, however there are currently limited industrial applications at low to medium TRL4 to 5. Membranes require fundamental research to understand transport at the atomic and molecular level, new computational design methods to develop novel triggers, and new membrane systems including smart/self-assembling/self-repairing systems and lower energy cost:

- Understanding the atomic- and molecular-level processes that affect separation performance in membranes, including mechanisms of neutral, ion, and electron transport through a membrane
- Computational methods and models to design and to optimise the separation of hierarchical structures, hybrid organic/inorganic structures, tailored functionalities, catalysts, and other features to enhance transport and selectivity, and improve stability
- New approaches for membrane separation and alternative driving forces or specific membrane-permeate interactions that can enable separations that are less energy-intensive than conventional temperature and pressure swings
- New concepts for the design of membrane separation systems, incorporating self-assembly and even self-repairing strategies, and/or multifunctional structures. New concepts that could

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incorporate hybrid or ‘smart’ materials that alter the transport of a targeted gas or ion on application of a specific external trigger

Priority: High

Facilities required:

- **Mobile units: on-site testing and training of technicians in operation, membrane and humidity management etc ≥TRL7**

Services:

- **Joint research**
- **Capacity building**
- **Knowledge sharing**

Sectors:

- **Energy from Waste**
- **Cement**
- **Steel**
- **Petrochemical**

CO_2 Utilisation - Research Priorities and Infrastructure Needs

CO_2 utilisation has not been included in ECCSEL’s research priorities until now. However by mid-2019 a consensus had been reached among ECCSEL ERIC members on the inclusion of CO_2 use facilities and extended its scope of interest to include CO_2 utilisation. In line with its mission to facilitate net-zero energy and industry, ECCSEL also defined the initial criteria against which CO_2 use technologies and facilities would be included in the RI. Initially, three main pathways were identified that offered clear strategic alignment with ECCSEL:

1. Thermochemical conversion and hydrogenation of CO_2
2. Electrochemical and photochemical conversion of CO_2
3. CO_2 conversion to solid carbonates

The value, compatibility and potential implications of extending ECCSEL's scope to include CCUS has since been assessed across two

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ECCSELERATE project deliverables: D1.3 Global CCU infrastructure and market assessment (Chavez and Partenie, 2020), and D1.4 Synergy potential of CO_2 utilisation and alignment strategy for CCUS (Chavez and Shinde, 2021). ECCSELERATE D1.4 looked at the potential for and opportunities of aligning CO_2 utilisation in view of ECCSEL's CCS scope, facilities and services, building on the preceding D1.3 where four types of CO_2 use were discussed; direct use, CCU fuels, CCU chemicals and polymers, and mineralisation. From ECCSEL's perspective, a prerequisite to consider CCU fuels, chemicals and materials as a viable CCU option was to assess their potential in terms of GHG emission reduction e.g. using a Life Cycle Assessment (LCA, Zimmermann et al., 2020). The two CCU deliverables conclude that CO_2 use involving mineralisation/carbonation aligns very closely with ECCSEL's immediate mission and priorities. Technologies for the production of CCU fuels and chemicals also align with ECCSEL's ambition to facilitate a sustainable circular decarbonised economy in the longer term.

High importance was placed on utilisation of CO_2 by all industries participating in the ECCSEL industry workshop series. The strong drive for CO_2 use was due to government decisions, perceived lack of storage possibilities, or the need for reassurance that available storage options would suit their needs. Industry focus was reported to be directed towards finding a variety of different options to avoid oversaturating markets with a single product. As a result, no single technology comes into focus as having clear research priorities that need to be addressed. However, chemical conversion of CO_2 to usable products like methanol, dimethyl ether, ethanol and polyols which can replace fossil-fuel derived products was generating most interest. For these products, high importance was placed on direct on-site conversion and intensified processes to produce high value products directly on-site, without the need for CO_2 transport. Not all industrial workshop participants had plans for specific products and processes they expect to focus on, but most expressed a strong need for research in this area.

Direct use of CO_2, e.g. as refrigerant, solvent, carbonating agent, fire extinguisher etc., where CO_2 is released into the atmosphere immediately after use and therefore has no climate change mitigation effect, is not aligned with ECCSEL's mission and objectives so remains outside ECCSEL's scope. It also emerged from the industry workshops that direct utilisation of CO_2 (e.g. pipelines to greenhouses, or as feedstock within industrial clusters) are only possible for specific locations and are already

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available at high TRL. Direct use of captured CO_2 is not taken further at this point, but will be kept under review, and ECCSEL's research priorities in CO_2 utilisation are constrained at this time to mineralisation, and to defossilised CCU fuels, chemicals and polymers with a broader view to supporting the development of smart integrated capture and utilisation concepts.

The following key research needs are identified, and are also summarised in the Executive Summary, Tables 3 and 4.

Mineralisation

Mineralisation of CO_2 is the conversion of CO_2 into cement, concrete/CO_2-cured concrete and carbonate mineral-based aggregates and waste-based carbonated aggregates that can be used in different applications. The outcome is near-permanent storage of CO_2, and a direct contribution to climate change mitigation by avoiding emission to atmosphere over-long term ($\geq 10^2$ year) timescales. This type of use is, clearly, closely aligned with ECCSEL's overarching mission and immediate priorities to facilitate net-zero energy and industry. Mineralisation also has enormous potential because it does not require high purity CO_2, the process is exothermic, and waste materials are converted into valuable products. In general, the following areas currently need research focus:

- Assess and improve mineralisation technologies
- Improve technologies that directly process flue gas, avoiding the need for purified CO_2

Priority: High

Facilities required:

- **Pilots**

CCU fuels, polymers and other chemicals

Fuels, chemicals, precursors and feedstocks such as methanol, DME, diesel and gasoline, and kerosene derived from captured CO_2 have the potential to replace fossil fuels in the maritime and aviation sector, as well as 'defossillising' the production of carbon-based chemicals and materials. If we accept that carbon-based materials will continue to be needed even in a net-zero future, moving to a new source of carbon aligns

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with ECCSEL's longer-term ambitions to support a sustainable circular economy. This is particularly the case where CO_2 is demobilised for decades or more (e.g. in relatively stable polymers), or where production energy requirements can be decarbonised, reduced or overcome.

ECCSEL research priorities should focus on:

- Identifying catalysts with high efficiency, stability, and reliability
- Converting CO_2-fuels through gas fermentation
- Addressing thermophysical challenges e.g. low CO_2 solubility in water

Priority: High

Facilities required:

- **Research facilities and pilot plants to review potential conversion**
- **Research demonstration plants: thermo-catalytical conversions ≥TRL7**
- **Mobile demonstration plants tot test at industrial conditions: of integrated capture and conversion system based on Point sources.**
- **Demonstration plants of integrated direct air capture and conversion system at relevant scale**

Services:

- **Joint research**
- **Capacity building**
- **Knowledge sharing**

Sectors:

- **Energy from Waste**
- **Cement and lime**
- **Steel**
- **Petrochemical**
- **Maritime**

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CO_2 Transport and Fluid Properties - Research Priorities and Infrastructure Needs

The major knowledge gaps that remain within CO_2 transport are in flow phenomena in pipelines, wells, and bulk transport vessels, at the interface to storage and to capture/conditioning, pipeline and tank integrity. Further, there is a need to develop methods and technologies for traceable flow metering and monitoring and control systems for CO_2 transport. Knowledge of the thermophysical and corrosive properties of CO_2 mixtures are needed in all these processes, as well as in capture, injection, and storage. Key CO_2 transport and fluid property research priorities, and corresponding infrastructure needs follow, and are summarised in the Executive Summary, Table 5.

Properties of CO_2 and CO_2 mixtures

Some impurities in CO_2 streams can be present at percentage levels and can therefore significantly affect thermophysical properties. Other components can be present in trace (i.e. parts per million) concentrations, and potentially affect phase behaviour and corrosive properties. There are significant gaps in the data sets of thermophysical properties of CCS-relevant CO_2-rich mixtures under CCS-relevant conditions. Research emphasis should therefore be placed on quantifying the properties to which model predictions are the most sensitive, such as phase equilibria (including high pressure and solids), density, heat capacity/caloric properties, speed of sound, thermal conductivity, interfacial tension, viscosity and diffusion coefficient. These properties have high importance in different parts of the CCS chain, and some of them are even more relevant for capture, storage, or interfaces, than they are for transport alone. Interfacial tension is, for example, an important property to predict flow through porous media. To achieve consistent CCS-chain models, the same property models should be used throughout. There is also a lack of data on the corrosive properties of relevant CO_2-mixture compositions for pipeline materials. Infrastructure priorities are therefore focussed on obtaining thermophysical data at CCS-relevant conditions, especially for CO_2 mixtures:

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- Optimise/improve the robustness of a number of processes within CCS, such as ship offloading, CCS pipeline transport, and low-temperature separation processes
- Accurate phase equilibria data in the temperature range between -60 and -130°C and up to 100 bar for mixtures
- Detection and analysis of solid and hydrate formation
- In-situ characterisation of phase and chemical equilibrium to study minor but reactive components e.g. amines, sulfuric components, NO_x, (possibly via upgrade of current -60 to 200°C ECCSEL facilities)
- Equations of state with high predictivity, highly accurate reference measurements of density, viscosity, and thermal conductivity
- Accurate equation of states for low temperature, high pressure CO_2 and CO_2 mixtures, specific heat capacity, and Joule-Thompson coefficient
- Accurate speed of sound for pure CO_2 and for CO_2 mixtures
- Interfacial tension at high pressure
- Thermal conductivity data for CCS-relevant pure CO_2 and CO_2-rich mixtures, especially liquid, and gas phase impurities, at reservoir-relevant temperatures, pressures, and chemical environments
- Liquid and gas phase diffusion coefficient data for process simulation and chemical absorber design, adsorption processes and membrane separation, and in reservoirs

Priority: High

Facilities required:

- **Phase equilibria: low-temperature (-130 to -30°C) and phase equilibria with solids**
- **Phase equilibria: new cells or upgrade of cells with in-situ capabilities and for demanding components**
- **Reference density meters for gases, low temperatures, and corrosive mixtures, co-located with accurate viscosity and thermal conductivity: single or dual sinker suitable for CCS-relevant corrosive mixed fluids at -60 to 200°C and at least up to 400 bar**
- **High accuracy flow calorimeter**
- **Speed of sound facility, e.g., doping and extrapolation with ultrasound meter, or spherical resonator at low frequency**
- **Interfacial tension facility for high pressure**

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- **Thermal conductivity facility, e.g., hot wire cooling at reservoir pressure and -60 to 200°C with aggressive components present**
- **Diffusivity of liquid and gas phase in CCS-relevant conditions**

Flow characterisation in pipelines and wells, ship transport

A facility is needed to characterise CO_2 flow conditions and geometries that lead to failure in process safety systems:

1. Pressure safety valves (PSVs) in process plants typically depressurize into a low-pressure stack, leading the fluid to a safe location for dispersion
2. Safety systems on CO_2 carriers will have a similar layout
3. Such systems have been/are being designed today, following existing codes and standards. However, there is a lack of experimental and theoretical verification of the appropriate functionality.

If these systems become blocked with dry-ice, the consequences can be catastrophic. It is therefore important to know the process and flow conditions and the geometries under which these systems fail. This is relevant for capture, transport, and injection. A facility for investigation of dry ice formation and impact downstream of a depressurisation is currently under construction by SINTEF Energy Research financed by the ECCSEL Research Infrastructure for Norwegian Full-Scale CCS (ECCSEL NFS) project. If included in ECCSEL ERIC, this new facility (FASafe) will partly address key research needs focussed around reliable and validated modelling tools needed to optimise the design and operation of CCS systems, while maintaining a high degree of safety. Some of the research needs comprise detailed characterisation of CO_2 horizontal flow, i.e.,

- Pressure drop
- Gas/liquid volume fractions
- Temperature
- Mass flow rate

CO_2 received into a network from multiple sources creates complexity for control and operations that needs to be understood through transient analysis. An ECCSEL facility has been established to acquire data upstream of a pipe depressurisation (DEPRESS) on the formation of solids. The following issues still need attention:

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- Characterisation of flow downstream of depressurisation, especially understanding formation of solids and related kinetics
- Clogging of safety equipment
- Loading low-pressure CO_2-transport ships
- Transient analysis for control and operation of networks handling CO_2 from multiple sources
- Transient vertical flow, e.g., in wells is relevant to start-up, shut-in, re-pressurisation, depressurisation, blow-out and also unloading of ships
- Critical processes relating to loading and unloading of ships
  - flexible hoses
  - flow control/metering
  - batch-wise versus continuous injection into reservoirs, and buffering systems, for offshore unloading
- Model validation for CO_2 flow

Priority: High

Facilities required:

- **Transient phenomena facility: FASafe now in construction via ECCSEL NFS**
- **Flow assurance in safety systems: FASafe will partly address**
- **Valve flow characterisation facility: flow and pressure drop in valve and choke geometries for CO_2-rich mixtures (combine with fiscal metering facilities)**

Pipeline and tank integrity

Commented [HTC1]: If polymer priorities stay within this RP, then rename RP to accommodate.

Pipeline integrity and containment of CO_2 are concerns safe operations and public acceptance. There is a need for data allowing the development and validation of accurate models for the prediction of running-ductile fracture in CO_2 pipelines.

- Detailed studies of thermophysical properties (mentioned above)
- Flow out of cracks in pipes and along opening pipe flaps
- Development of more accurate models for forces acting during running-ductile fracture

Priority: Medium

Facilities required:

- **Accurate facility for investigation of corrosion: larger number of impurities and lower concentrations (upgrade ECCSEL NFS IFE corrosion facility?)**
- **Facility for fracture propagation control (FPC) tests of subsea CO_2 pipelines: medium- and full-scale burst tests to validate design tools for FPC of CO_2 pipelines (existing onshore facilities in Norway, UK, and Italy are not part of ECCSEL)**
- **Pressure distribution on pipe flanks and flaps during release of boiling CO_2: geometry representative of pipe crack during a running-ductile fracture**

Compatibility of non-metallic components in CO_2 value chain

Non-metallic polymers in gaskets of valves and meters, composite pipes, flexible pipes for ship offloading, and inner coatings are likely to be in contact with CO_2 and CO_2 mixtures throughout the CCS value chain. There is a need to better understand the stability and performance of non-metallic polymers (thermoplastic, elastomer, and thermosetting) components of the CO_2 transport network in contact with CO_2 and CO_2 mixtures.

- Molecular structure and CO_2 solubility in polymers
- Impact of CO_2 impurities on polymer components
- Extraction of low MW components from the polymer phase, changing the physical and chemical properties of the polymer (elastomers)
- Effect of rapid gas decompression (RGD) on integrity of non-metallic exposed to CO_2 and stability towards dynamic loadings (elastomers/thermoplastics)
- Effect of CO_2 on polymer coatings for metal pipelines (swelling, delamination, possible debris detachment)
- Barrier performance and suitability of existing risers used in flexible pipes when in contact with dense phase CO_2.

Priority: Medium

Facilities required:

- **Facility for exposure and RGD of polymer to CO_2 up to 300 bar: measurement of swelling and physical integrity.**
- **Test rig for determination of CO_2 solubility in polymers for dense phase and liquid CO_2.**
- **Model for prediction of polymer/CO_2 compatibility under relevant operating conditions**

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Non-equilibrium phenomena

Boiling liquid expanding vapour explosions (BLEVE) is a phenomenon that might be relevant for safety studies of CO_2 systems, especially if CO_2 is transported in a liquid state at pressures above about 40 bar, as in CCS. Safety implications associated to BLEVE are of the utmost relevance. Enhanced understanding how CO_2 behaves during fast pressure changes is key. Experimental studies involving non-equilibrium phenomena are required to advance in this subject.

The kinetics of solid CO_2 formation and melting/sublimation mentioned above is also a non-equilibrium phenomenon. Data will underpin the development of transient multiphase flow models specifically of running-ductile fracture in transport pipes, but is not limited to CO_2 transport.

Priority: High

Facilities required:

- **BLEVE wave structures**
- **Kinetics of solid formation, sublimation, melting**
- **ECCSEL NFS FASafe facility**

Fiscal metering

Carbon dioxide poses specific challenges for flow metering since the particular properties of CO_2, whose critical point is close to the operational conditions, mean that they change rapidly with changes in temperature and pressure. Sound attenuation is higher than in many other fluids, which could affect the feasibility of ultrasonic time-of-flight (TOF) meters commonly used for natural gas. Currently, the only technology with published studies claiming accuracies below the ETS requirement (1.5%) is Coriolis, but this is only for pure CO_2 and at flow rates/dimensions far below that required in CCS. For CO_2 with impurities, results at the same scale have not been verified with sufficient accuracy. There is hence a need for a loop for traceable tests of flow meters at an industrially relevant scale.

Priority: High

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Facilities required:

- **Large scale test facility:**
  - **test technologies for fiscal or custody transfer flow metering under controlled conditions and fluid compositions in industrially-relevant conditions**
  - **flow rates at least a few hundred tonnes/hour**
  - **4 to 40°C, up to 120 bar**
  - **flow calibration to a gravimetric reference**
  - **pressure, temperature, and fluid density measurement**
  - **ideally expandable to fiscal metering of CO_2-rich mixtures**

Flow monitoring and control

While early strategies for CCS focused on capturing CO_2 from fossil fuel power plants, there has been an increasing awareness of CO_2 capture from industrial sources being at least as important. Clusters of industry sources, established to reduce costs through economics of scale, will evolve into complex CO_2 transport networks with large local and temporal variations in flow rates, conditions, and impurity contents, and with distinctively different flow assurance challenges than in natural gas transport. Some of the anticipated impurity species may, even at low concentrations, strongly affect the threshold for formation of an impurity-rich second phase, calling for an advanced monitoring and control system to avoid off-spec and undesirable flow conditions. There is a need to mature current flow control systems to these particular challenges of CCS transport:

- Advancement of the underlying thermo- and fluid dynamic models
- Online and interconnected instrumentation to measure composition and the onset of phase separation
- Verification of instrumentation at an industrially relevant scale

Priority: High

Facilities required:

- **Test loop: controlled multiphase and multicomponent flow at sufficient scale (possible synergies with a test facility for fiscal metering) to test flow monitoring instrumentation**

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CO_2 Storage - Research Priorities and Infrastructure Needs

Since the publication of the ECCSEL Research Strategy Roadmap (Pearce et al., 2017), three main changes have affected the research needs for CO_2 storage:

- Increased emphasis on integration of CCS into a rapidly evolving energy landscape e.g. complementary and challenge aspects with hydrogen, energy storage, geothermal
- Focus for CCS on capture from industrial sources rather than fossil fuel power plants (impact of growing renewables on market share)
- Emphasis on (a degree of) utilisation as a pathway to reduce costs and as a storage option

However, the need for more efficient and cost-effective storage remains and, as such, many of the key research needs identified in the first iteration of ECCSEL Strategy Roadmap require additional attention.

The political and regulatory landscape has also changed, although the countries where political support for CCS was high remain key actors in the deployment of CCS projects. EU and national strategies, roadmaps and funding programmes are described in Czernichowski-Lauriol (2021). Nationally Determined Contributions (UNFCCC, 2021) set out country efforts to reduce emissions and adapt to climate change and are reported to UNFCCC every five years, with the latest round of NDCs submitted by 2020, some include CCS.

Mission Innovation, an international initiative, identified a number of Priority Research Directions for CO_2 storage during 2017 (Mission Innovation, 2021). These focused on achieving gigatonne/year capacity and injectivity, effective monitoring for assurance and site closure, improving characterisation of faults/fractures, well integrity, and managing the risk of induced seismicity.

The SET-Plan TWG9 CCS and CCU Implementation Plan sets out the actions required to achieve the ten targets envisioned in 2017 (CCUS SET-Plan, 2020a), with a 2020 update sheet (CCUS SET-Plan, 2020b).

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The Implementation Plan focuses on delivery of a full chain CCS project and CCS and CCU, developing a CO_2 storage atlas, advancing improved monitoring and verification techniques, and unlocking European storage with pilot projects and FEED studies. Research and innovation priorities are highlighted in a 2020 report (CCUS SET-Plan, 2020a), including investigation of the role for CCS in enabling clean hydrogen and the role and feasible scale for negative emissions. Utilisation and the circular economy to add value to CO_2 has also become a topic of interest and CO_2-EOR is being actively considered (e.g. MOL, the national oil company in Hungary (Bellona, 2011), as is how to trap CO_2 for long-term storage, in building materials (see also the dedicated chapter CO_2 Utilisation - Research Priorities and Infrastructure Needs).

The EC CO_2 Storage Directive (European Commission, 2018) has been in place for over a decade and a number of appraisal and storage permits have been requested under this regime and, through this process, additional points for clarification have been identified that could usefully be tackled through research projects. The Zero Emissions Platform, ZEP, has recently published recommendations for improved clarity around the Guidance Documents based on experience from storage projects and permit applications (ZEP, 2022).

In Europe, funding programmes such as Horizon 2020, the ERA-Net ACT programme and the Clean Energy Partnership (CETP) all aim to enable research and development activities to accelerate the deployment of CCUS.

The main research needs in CO_2 storage are centred around improving efficiency of CO_2 injection and storage operations and reducing costs through cost-effective site assurance that demonstrates safe and permanent containment and ensures that risks are appropriately managed. Responding to these research needs will help accelerate the roll-out of CCS. CO_2 storage is up and running, the aim now is to streamline processes, improve efficiency and reduce costs.

There are, of course, cross-cutting issues that are critical for CCS but perhaps not related to the scientific questions being addressed through ECCSEL. For example, through links to initiatives such as IPEM (International Platform for Environmental Monitoring, a legacy initiative of the H2020 SECURe project, https://www.securegeoenergy.eu/) which draws together CO_2 storage testbeds, public engagement opportunities could be sought.

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There are currently no operational pilots CO_2 storage projects within the scope of ECCSEL; Hontomín is paused, Ketzin is abandoned as planned. Only the Sleipner site offers injection data for a large saline aquifer, and this site is a confined aquifer. A scoping study for a UK CO_2 Storage pilot is underway (BGS, 2020). A potential pilot project is being developed in the Czech republic (CO_2SPICER, 2022). CO_2GeoNet (2021) considered the overall picture of how CCS is developing in Europe, including research and pilot projects. Laboratory-scale facilities are relatively common and a range of pilot scale facilities are planned and the infrastructure proposed below would complement existing facilities, advancing knowledge in terms of increasing the range of geological settings and operational scale for which data are available, moving towards large-scale implementation. Development of some Measurement, Monitoring, Verification and Quantification (MMVQ) technologies, particularly permanently installed sensors, are relevant to several pilot/testbeds described.

Research priorities related to the storage of CO_2, and corresponding research infrastructure requirements are set out below, and in the Executive Summary,

Table 6.

Site selection and demonstrating security of storage

Demonstration of safe storage is a key area of interest, with a focus on satisfying regulators that the storage site and potential risks can be managed, and on demonstrating that the site behaviour is well understood. This includes understanding potential leakage mechanisms/pathways, and demonstrating that risks can be managed in a cost-effective manner.

Site characterisation and modelling for hydrocarbon recovery is well-established, however, for storing CO_2, the site is being considered for long-term storage of a buoyant fluid, rather than fluid extraction. CO_2 storage requires cost-effective site characterisation that enables understanding of how the subsurface will respond and assurances on long term site integrity.

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Current topics of interest include understanding what data are required to satisfy regulatory and permitting requirements as well as to confirm that the storage potential can be utilised in a cost-effective manner.

Impacts on the over and under-burden are particularly relevant given public concerns over the risk of induced seismicity relating to activities in the subsurface. Where CO_2 is stored in depleted hydrocarbon fields, the impacts of repeated stress cycles on caprock integrity are relevant.

Potential leakage pathways remain a topic of interest, in particular geological pathways. Research topics include more effective detection, monitoring and modelling of faults as well as modelling and understanding behaviour of faults and the interaction of CO_2 with faults.

Optimising use of resources extends to use of the (sub)surface for net-zero, considering synergies and challenges around multiple uses of the subsurface and interactions with other actors for the transition to net zero.

Priority: Medium-high

Facilities required:

- **Testbed or pilot: fault permeability, aquifer**
- **Testbed: long term fault permeability**
- **Testbed: failure of reservoir and caprock or under-burden integrity**
- **Testbed: low integrity caprock**

Dynamic storage capacity; understanding the pressure-connected volume and modelling the storage complex

Topics around fully understanding the dynamic storage capacity of a storage site include pressure-connected volume, pressure management techniques and improved modelling techniques.

This topic requires both improvements in modelling techniques and practical investigation.

Improvements in dynamic modelling could include improved integration of different disciplines (geochemical, geomechanical and flow modelling) and improved understanding of the impacts of multiple fluids and phases. Integration models at different scales (high resolution site models and regional models) and improved representation of heterogeneities are also relevant here.

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To satisfy regulatory and permitting requirements, demonstrating a thorough understanding of the site is essential. Site models evolve over time, and more examples of how this understanding evolves over time would provide valuable input to conversations around storage permitting. In particular, for saline aquifers where there is no history of fluid extraction to assist in modelling how the CO_2 plume and pressure footprint would be expected to evolve.

Understanding how much of the available storage potential can be utilised in a cost-effective manner is essential to getting CCUS projects deployed. Improved understanding of the behaviour of CO_2 and subsurface pressure, particularly for saline aquifers where pressure has not been reduced through hydrocarbon extraction, remains a topic of interest. Other aspects for investigation include consideration of where pressure management through brine extraction may be required and how this would work in practice, impacts of heterogeneities in the subsurface, and interactions between multiple CO_2 storage projects in close geographical proximity.

Priority: High

Facilities required:

- **Model/monitoring loop and site assurance: improved integrated modelling, real thermophysical data**
- **Pressure pilot: saline aquifer and interactions between multiple injections**
- **Injection pilot: compartmentalised/heterogeneous saline aquifer**

Storage optimisation through development of a range of injection strategies

This priority focusses on improved injection to reduce costs and improve storage efficiency. This includes upscaling to understand how to test representative pore volumes for many km^2 and long periods (more than a few hours) from weeks to months and how to predict the size of the pressure-connected volume that is in reach of one well, especially in saline aquifers.

The impacts of programmes of variable injection that could accommodate variations in flow rates as e.g. more sources come online/CO_2 is redirected for utilisation/variations in demand for products that produce

CO_2, are a growing topic of interest as CCS moves from single isolated projects towards an integrated pan-European CO_2 management network. This required flexibility would be expected to impact CO_2 storage operations.

Understanding the behaviour of CO_2 in the well and near-well environment is important to optimise storage efficiency and to reduce energy demands for CO_2 storage operations.

Priority: High

Facilities required:

- **Laboratory: multiphase flow, real thermophysical data**
- **Pilot: enhancing storage injection rates and capacity, predicting and modelling pressure-connected volume in saline aquifers**
- **Testbed: well issues and CO_2 behaviour**

Monitoring for assurance and long-term containment

Low cost, effective long-term monitoring strategies were highlighted for investigation.

This includes more efficient cost-effective monitoring techniques to demonstrate reservoir behaviour and provide storage assurance, detection of unexpected storage site responses, and identifying and quantifying leakage in the unlikely event this were to occur.

These monitoring aims would also be supported through improved data management applications (e.g., providing real-time data, integration of different data streams for site management, automatic alerts, machine learning for data processing and interpretation).

The impacts of CO_2 operations on wells and well completion materials is also a topic of interest, as well as considerations on how to monitor well integrity in the longer term, including during and after site closure.

Priority: Medium-high

Facilities required:

- **Permanent/continuous monitoring, non-invasive techniques, low maintenance/operational demand**
- **Data management: real-time data management, automatic alerts, machine learning for data processing and interpretation**

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Priority: Medium

Facilities required:

- **On/offshore testbed: on/offshore tool development for leakage detection and measurement**
- **Multi-sensor platforms**
- **Laboratory: wellbore material reactions**
- **Field laboratory: wellbore completion**

Developing remediation and mitigation techniques

Technology transfer from other industrial applications leaves CO_2 storage-specific research questions. The practical application of remediation techniques to CO_2 storage requires testing at small scale facilities to move techniques to a higher Technology Readiness Level and to prepare for deployment, should remediation techniques be required at full scale CO_2 storage sites.

Priority: Medium-high

Facilities required:

- **Testbed: practical remediation technique testing**

Storage permitting

At this stage, practical experience in successfully obtaining a storage permit with relevant financial assurances, providing assurance during operation, and reaching agreement on post-closure monitoring and handover is extremely limited. This is frequently identified by storage operators as a significant barrier to deployment:

- Pilot scale storage project could potentially be used for a 'dry run' to inform discussions with the relevant authorities on meeting the requirements on the Storage Directive that are proving challenging, in particular
  - Liability and risk management
  - Demonstrating that the site is ready for handover and post-injection monitoring

Priority: High

Facilities required:

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- **Pilot: storage of moderate quantities of CO_2**

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