SET-Plan ACTION n°9 - Implementation Plan – 21 09 2017

SET-PLAN TWG9 CCS and CCU Implementation Plan

Introduction

The SET-Plan TWG9 CCS and CCU Implementation Plan outlines 8 key Research and Innovation (R&I) Activities, required to achieve the ambitious targets for CCS and CCU for 2020 agreed by the European Commission, SET-Plan countries, and industry, outlined in the 2016 Declaration of Intent.[1] The Implementation Plan also identifies the ongoing actions which will be required to meet the Key Performance Indicators which have been set for 2030. The membership of the TWG9 comprises of 11 SET-Plan countries (the Czech Republic, France, Germany, Hungary, Italy, Norway, the Netherlands, Turkey, Spain, Sweden and the UK), industrial stakeholders, non-governmental organisations and research institutions.

Key learnings from the Implementation Plan

The TWG9 Implementation Plan sets out the actions required to achieve the 10 targets for CCS and CCU, as introduced above. It identifies ongoing projects under each R&I Activity and proposes new actions to address gaps where the existing projects are seen to be insufficient to achieve these targets within the 2020 timeframe. This includes gaps in the funding instruments currently available from both Member States and the European Union, required to progress a number of ongoing and proposed CCS and CCU projects.

In the past both EU and state funding instruments have had very limited success in delivering progress on CCS demonstration projects in Europe. A key example is the estimated €2.1 billion of funding made available through the 2 NER300 calls in 2012 and 2014. The completion of a comprehensive Implementation Plan for CCS and CCU now presents a timely opportunity to assess how existing, as well as planned sources of funding, such as the Innovation Fund, and funding programmes under the new Multiannual Financial Framework (MFF) for after 2020, need to be designed so they can successfully support projects and achieve the deployment of low-carbon technologies in Europe. There are also opportunities to support projects through Horizon 2020 funding, which is an important enabler of CCS and CCU in Europe. Current proposals under the 2018/19/20 Energy Work

[1] SET-Plan Declaration of Intent on strategic targets in the context of Action 9 'Renewing efforts to demonstrate carbon capture and storage (CCS) in the EU and developing sustainable solutions for carbon capture and use (CCU)' (European Commission, 2016)

Programme now show good alignment with the ongoing and proposed activities identified within the Implementation Plan.

A further issue raised by the TWG9, and outlined within the Implementation Plan, is the current status of the London Protocol. This prohibits the export of CO_2 from a contracting party to other countries for injection into sub-seabed geological formations. The protocol was amended in 2009 to enable cross-border CCS projects, but the amendment must be ratified by two-thirds of contracting parties to enter into force. Given the required number of ratifications and difficulties associated with the ratification process, it appears unlikely that two-thirds of contracting parties will be in a position to ratify the amendment in the near term. Raising awareness among relevant government ministries of the importance to global CCS deployment of ratifying the London Protocol amendment should be a priority. There are interim solutions to address this barrier and consideration should be given to options identified by the International Energy Agency[2] that may be available to contracting parties under international law to address this barrier to CCS deployment pending formal entry into force of the 2009 amendment.

Another major risk to the delivery of one of the targets, are the recent developments in the ROAD project. The delivery of Target 1 – to have at least one commercial-scale, whole chain CCS project operating in the power sector in 2020 - will be very unlikely. The 2030 target should be carefully assessed over the course of the next two years, also taking into account the integrated national energy and climate plans for after 2020 prepared as part of the Energy Union Governance.

Proposal for further work

The monitoring and follow up of the execution of the IP will be carried out by the SET Plan Steering Group members of the Action 9 TWG. This will be ensured by the co-chairs by the TWG.

The EC intends to facilitate through a Coordination and Support Action (CSA) the coordination activities needed for the execution of the Implementation Plan on CCUS.

In order to continue the momentum and delivery of the work so far, the co-chairs will organise meetings as necessary in order to strengthen the Implementation plan activities and commitments from the different actors. It is envisaged that the aims of this work could be twofold:

1. Maintaining a dialogue between the European Commission and the SET-Plan countries and stakeholders involved in the TWG9 to ensure that the actions needed to progress the CCS and CCU activities outlined in the Implementation Plan can be identified and addressed.
2. Monitoring the progress of the actions outlined under the Implementation Plan, including the 'monitoring mechanisms' towards 2020 and beyond.

Guide to the Implementation Plan structure and terms

The structure of the Implementation Plan is based on the guidance of the European Commission's Common Guiding Principles document, outlined by the SET-Plan Steering Committee. Whilst a number of the projects listed are expected to be operational within the 2020 timeframe, the long timescales involved in developing CCS projects mean that the progress of the activities identified may range from the completion of feasibility studies, up to the final investment decision by this date. To ensure that the momentum of projects, as well as the supporting policy actions, is not lost, proposals are included for actions needed beyond 2020, based on the '2030 Key Performance Indicators' set out in the Declaration of Intent.[3] This will require continued support from industry, SET-Plan countries and

[2] Carbon Capture and Storage and the London Protocol (IEA, 2011)

[3] SET-Plan Declaration of Intent on strategic targets in the context of Action 9 'Renewing efforts to demonstrate carbon capture and storage (CCS) in the EU and developing sustainable solutions for carbon capture and use (CCU)' (European Commission, 2016)

the European Union through successor programmes to Horizon 2020, including through future R&D strategies proposed under Framework Programme 9.

Within this document monitoring mechanisms refer to key milestones for each project/action included under the R&I Activity, which will contribute to delivering the relevant SET-Plan target. Deliverables refer to projects or actions which will deliver the relevant SET-Plan target.

Contents

Targets for CCS and CCU under the SET-Plan Action 9

The agreed specific targets addressed in this Implementation Plan have been defined in the Declaration of Intent under SET Plan Action 9:

Target 1: At least one commercial-scale, whole chain CCS project operating in the power sector

Target 2: At least one commercial scale CCS project linked to an industrial CO_2 source, having completed a FEED study

Target 3: SET Plan countries having completed, if appropriate in regional cooperation with other MS, feasibility studies on applying CCS to a set of clusters of major industrial and other CO_2 sources by 2025-2030, if applicable involving cooperation across borders for transporting and storing CO_2 (at least 5 clusters in different regions of the EU)

Target 4: At least 1 active EU Project of Common Interest (PCI) for CO_2 transport infrastructure, for example related to storage in the North Sea

Target 5: An up-to-date and detailed inventory of the most suitable and cost-effective geological storage capacity (based on agreed methodology), identified and accepted by various national authorities in Europe

Target 6: At least 3 pilots on promising new capture technologies, and at least one to test the potential of sustainable Bio-CCS at TRL 6-7 study

Target 7: At least 3 new CO_2 storage pilots in preparation or operating in different settings

Target 8: At least 3 new pilots on promising new technologies for the production of fuels, value added chemicals and/or other products from captured CO_2

Target 9: Setup of 1 Important Project of Common European Interest (IPCEI) for demonstration of different aspects of industrial CCU, possibly in the form of Industrial Symbiosis

Target 10: By 2020, Member States having delivered as part of the Energy Union Governance their integrated national energy and climate plans for after 2020, and having identified the needs to modernise their energy system including, if applicable, the need to apply CCS to fossil fuel power plants and/or energy and carbon intensive industries in order to make their energy systems compatible with the 2050 long-term emission targets

Research & Innovation Activities

The SET-PLAN TWG9 has identified 8 Research and Innovation 'R&I' Activities required to deliver the 10 agreed targets listed under the Declaration of Intent on strategic targets in the context of Action 9 'Renewing efforts to demonstrate carbon capture and storage (CCS) in the EU and developing sustainable solutions for carbon capture and use (CCU)'. The actions contained under each of the R&I activities comprise of ongoing projects, in addition to proposals for additional actions required to meet targets.

R&I activities outlined in detail within this paper, and summarised below:

R&I Activity 1: Delivery of a whole chain CCS project operating in the power sector (target 1)

R&I Activity 2: Delivery of regional CCS and CCU clusters, including feasibility for a European hydrogen infrastructure (targets 2 & 3 and 10)

R&I Activity 3: EU Projects of Common Interest for CO_2 transport infrastructure (target 4)

R&I Activity 4: Establish a European CO_2 Storage Atlas (target 5)

R&I Activity 5: Unlocking European Storage capacity (target 7)

R&I Activity 6: Developing next-generation CO_2 capture technologies (target 6)

R&I Activity 7: CCU Action (targets 8 & 9)

R&I Activity 8: Understanding and communicating the role of CCS and CCU in meeting European and national energy and climate change goals (target 10)

These R&I activities outline the actions required to meet the 2020 targets. However, further CCUS development post-2020 is also required. Comprehensive R&I activities need to take place now in order to reach the Key Performance Indicators for 2030 listed in the Declaration of Intent under SET Plan Action 9. Ambitious R&D activities are already taking place under Horizon 2020, the ERA NET Co-fund ACT[4] and within national R&D programmes in several Member States. Furthermore, R&D infrastructure is built and operated in the ESFRI project ECCSEL[5], which has now proceeded to become a European Research Infrastructure Consortium (ERIC). All these activities should be strengthened onwards to 2020 in order to reach long-term CCUS ambitions.

Flagship activities

A number of Flagship Activities have been proposed, defined under the SET Plan Common Principles as a best example of how an R&I activity may deliver targets. 5 Flagship activities have been identified:

Flagship activity: Establish a CCS hub/cluster (including projects in the Netherlands, Norway and/or the UK)

A number of CCS clusters are currently being progressed in SET-Plan countries, linking a range of CO_2 emissions-intensive industries. These clusters may also be supported by the development of pan-European CO_2 infrastructure through the establishment of a Project of Common Interest (PCI).

[4] ACT – Accelerating CCS Technologies, www.act-ccs.eu
[5] ECCSEL – European Carbon Dioxide Capture and Storage Laboratories Infrastructure, www.eccsel.org

Flagship project: Fos-Berre/Marseille CCU cluster

The Fos-Berre/Marseille CCU cluster aims to offer a supporting scheme for high-emitting industries in the region to reduce their CO_2 emissions, developing a wide range of CCU technologies, including chemicals, material and fuel production, and supported through industrial and public funding partnerships. A feasibility study was completed in 2013 with the aim of finding synergies between industrial emitters and potential CCU pathways, sustaining the industries in the area by reducing their CO_2 emissions. At present, the cluster will focuses solely on CCU aspects; however, there are also plans to evaluate the potential opportunities for offshore storage in the future. The initial study was based on a collection of emission data and an analysis of the evolution scenarios of the various industrial sectors in the Fos-Berre-Beaucaire-Gardanne area and the infrastructure required (pipeline collecting CO_2 from different sources and feeding different applications).

Flagship activity: Progress Projects of Common Interest (PCIs)

The establishment of a Projects of Common Interest (PCI) under the 2017 European Commission call may act as a starting point for a European CO_2 transport infrastructure network, also supporting the development of regional CCS and CCU clusters.

Flagship activity: Establish a European CO_2 Storage Atlas

The establishment of a European CO_2 Storage Atlas will assist project developers and relevant permitting authorities to prioritise the most prospective areas for both onshore and offshore CO_2 storage, and will enable the design and development of transport infrastructure to be optimised.

Flagship Activity: Storage appraisal

Storage appraisal activities will build on the prospecting opportunities identified in the European CO_2 Storage Atlas, with the aim of expanding European experience of CO_2 storage, considering geographical balance, in addition to a range of storage options and injection volumes.

R&I Activity 1: Delivery of a whole chain CCS project in the power sector

*Responds to **Target 1**: At least one commercial-scale, whole chain CCS project operating in the power sector*

Overview of existing and planned activities

Progression of activities leading on from the ROAD project

The Rotterdam capture and storage project – abbreviated ROAD – would have been a full-chain CCS project storing CO_2 captured at a coal-fired power plant at Maasvlakte in the Port of Rotterdam. The Dutch government has provided €150 million of funding to facilitate the project. The project also has €180 million of funding from the European Energy Programme for Recovery (EEPR) fund. The project plan has undergone a number of changes since the project was first designed, including a change of storage location. A final investment decision (FID) was planned for the end of 2017 by the ROAD partners, depending on a number of national political factors. Recently, the two mother companies of ROAD made public their decision to end their financial support for the project. Consequently the grant agreement between the project and the European Commission will need to be terminated unless a viable alternative solution is found in the course of autumn 2017.

Progress of the Port of Rotterdam CCS and CCU cluster and other actions which may build on the work of the ROAD project

The Port of Rotterdam is well positioned for the development of a Western Europe CO_2 Hub, connecting offshore storage fields with emissions from Dutch heavy industry, and potentially other regions, including Antwerp and the Ruhr region in Germany. The development of this hub can be based on the actions already taken and knowledge already build up in the ROAD project.

Precombustion CCS in the power sector

In July 2017 Statoil announced that they are one of three partners (alongside Vattenfall and Gasunie) evaluating options to convert part of the Magnum gas plant in the north of the Netherlands into a hydrogen-powered plant. The project will also consider potential business models and transport and storage options, linked to the proposed PCI project (outlined further under R&I Activity 3). Captured CO_2 will potentially be transported by ship to Norway, and then transferred offshore by pipeline. First injection of CO_2 is currently expected to take place around 2023, expanded to accommodate additional volumes shortly afterwards through the development of additional offloading facilities in Norway.

Identified gaps

If there is a decision not to progress on the ROAD project, no other CCS power project has been identified in SET-Plan countries which can be delivered by 2020, meaning that achieving Target 1 set out in the Declaration of Intent will no longer be possible within this timeframe. To increase the robustness of deliverables under R&I Activity 1, supporting the application of CCS in the power sector, it will be necessary to progress development on a number of additional projects, including the Magnum project introduced above. Although these projects would not be operational before 2020, there is still significant development work which could take place in the intervening period, including initial feasibility studies for the additional CCS projects in the power sector required to meet the 2030 targets outlined in the Declaration of Intent (see Table 1.a.).

Pathway to 2030 and beyond

To realise the 2030 Declaration of Intent KPIs[6] of 10 commercial scale CCS projects in the power sector it is necessary to commence delivery of the next generation of projects, particularly those aimed at retrofitting existing power plants, and projects located in planned regional CCS and CCU clusters (see R&I Activity 2). The development of CCS projects in the power sector can take 7 to 10 years. Therefore, in order to realise 2030 objectives work on additional projects must be progressed as soon as possible, including an assessment of the opportunities available to retrofit existing assets in the power sector.

Table 1a: DOI Targets and Monitoring Mechanisms

DOI Target	**Monitoring mechanisms**
Target 1: At least one commercial-scale, whole chain CCS project operating in the power sector	• Establishment of a joint Horizon 2020 project to commence the delivery of the next generation of projects in the power sector
Pathway to 2030 and beyond	**Monitoring mechanisms**
10 commercial scale CCS projects in the power sector	• Progression of the next generation of CCS projects in the power sector • Policies established to support application of CCS in the power sector, linking to recommendations under R&I Activity 8 • Assessment undertaken of the opportunities available to retrofit further assets in the power sector

Expected deliverables and timeline

Progression of activities leading on from the ROAD project:

The ROAD project would have been the first application of CCS in the power sector in Europe and would have enabled visibility on costs of CCS and provided experience / cost reduction that could have supported subsequent phases of CCS. In addition, successful delivery of the ROAD project would have demonstrated how existing coal power plants could be retrofitted with CCS. Now since this project is unlikely, the following deliverables will contribute towards Target 1:

- Assessment of opportunities to retrofit existing assets by **2020** and beyond [ongoing].

Progress of the Port of Rotterdam CCS and CCU cluster and other actions which may build on the work of the ROAD project:

The Port of Rotterdam Authority will work with project partners, like ROAD, to support CCS and CCU developments, and initial parts of the cluster are expected to be operational by **2020/21** [ongoing]. Once operational this will deliver the following:

- Create an open backbone CO_2 pipeline in the Port of Rotterdam, in order to connect Offshore Storage fields, Users of CO_2 and Sources of CO_2
- Connecting sources/companies capturing CO_2 to a shared 'CO_2 backbone' pipeline

[6] SET-Plan Declaration of Intent on strategic targets in the context of Action 9 'Renewing efforts to demonstrate carbon capture and storage (CCS) in the EU and developing sustainable solutions for carbon capture and use (CCU)' (European Commission, 2016)

- Connecting Offshore Storage fields with the Port (Connection area / interface between land/port and sea)
- Re-use of CO_2 in order to attract strategic investment from companies/industries to strengthen the local clusters (e.g. EOR, building blocks for chemical processes, Green Houses)
- Connection possibilities to other regions in order to support them in lowering their local CO_2 footprint

CCS projects will be further assisted by the removal of certain legislative and administrative barriers. One such example is the Dutch Mining Law, which was amended in 2016 and came into effect on 1st January 2017, enabling simultaneous hydrocarbon production and permanent CO_2 storage in the same reservoir at the same time. This progress will address some of the existing barriers to CCS and build experience with the regulatory framework and will support the development of subsequent CCS projects to meet 2030 targets [ongoing].

Table 1b: Financing of planned activities to 2020

It is unsure which funds may be available for alternative CCS demonstration projects.

Parties	**Implementation Instruments**	**Indicative financing contribution**
Initially planned funding for the ROAD project		
European Commission	European Energy Programme for Recovery (EEPR)	€180 million *STATUS: Confirmed*
Member States and the European Commission	Horizon 2020	Up to €60 million The European Commission proposes this project for the Horizon 2020 Energy Work Programme for 2018/19, with several countries already being committed to financially contribute. *STATUS: Proposed*
Dutch Government	State funding	€150 million *STATUS: Confirmed*
GCCSI	Funding agreement	€4.3 million *STATUS: Confirmed*
Uniper and Engie (owners of the ROAD Project)	Private funding	€100 million (€50 million each) *STATUS: Withdrawn*
Port of Rotterdam	Co-investor[7]	€15 million *STATUS: Confirmed*
Progress of the Port of Rotterdam CCS and CCU cluster		
See 'Financing of planned activities to 2020' table under R&I Activity 2: Delivery of regional CCS and CCU clusters, including feasibility for a European hydrogen infrastructure		**Total budget required:** €485-520 million *(excluding contributions from the Port of Rotterdam)*

[7] The Port of Rotterdam is contributing to the project by building an onshore pipeline for transporting the CO_2. This work is outside of the scope of the ROAD project and therefore the costs of €15 million are also excluded from the total budget

Table 1c: Financing of planned activities to 2030

Parties	**Implementation Instruments**	**Indicative financing contribution**
Regional concepts developed to identify prospective CCS power projects which may be progressed, particularly opportunities to retrofit existing assets.	Mixture of private sector, national and EU instruments can be used to progress developments.	Funding for 5-10 pre-FEED studies for CCS projects in the power sector. Estimated cost of around €8–14 million per study. *STATUS: Proposed*
Member States, private sector, European Commission	State funding Connecting Europe Facility Innovation Fund	CCS projects will be eligible for funding under a future EU ETS Innovation Fund, with the detailed rules for this fund currently being developed. *STATUS: Proposed*
EERA CCUS to Contribute towards R&D actions		
Progression of additional CCS projects to construction/retrofit stage	To be determined	Total budget will depend on outcomes of the ROAD project and number of additional projects progressed
		Total budget required: to be determined

R&I Activity 2: Delivery of regional CCS and CCU clusters, including feasibility for a European hydrogen infrastructure

Responds to ***Target 2****: At least one commercial scale CCS project linked to an industrial CO_2 source, having completed a FEED study,* ***Target 3****: SET Plan countries having completed, if appropriate in regional cooperation with other MS, feasibility studies on applying CCS to a set of clusters of major industrial and other CO_2 sources by 2025-2030, if applicable involving cooperation across borders for transporting and storing CO_2 (at least 5 clusters in different regions of the EU), and* ***Target 10****: By 2020, Member States having delivered as part of the Energy Union Governance their integrated national energy and climate plans for after 2020, and having identified the needs to modernise their energy system including, if applicable, the need to apply CCS to fossil fuel power plants and/or energy and carbon intensive industries in order to make their energy systems compatible with the 2050 long-term emission targets.*

Overview of existing and planned activities

Norwegian CCS cluster

The ambition of the Norwegian Government is to build a full scale CCS demonstration project, operational by 2022. Feasibility studies have been concluded and conceptual studies started in early 2017. Three industrial partners have completed studies of CO_2 capture; capture of flue gas at cement production site in Breivik (Norcem AS), three sources at the ammonia plant in Porsgrunn (Yara Norge AS), and a waste incinerator at Klemetsrud (Waste-to-Energy Agency in Oslo). Gassco has studied options for pipeline and ship transport of CO_2 and Statoil has studied three sites on the Norwegian Continental Shelf for storage.

Rotterdam CCS and CCU cluster

The envisaged Rotterdam CO_2 hub at the Port of Rotterdam will collect emissions from industrial sources and transfer and store these offshore in the North Sea, with significant synergies with the ROAD project (see R&I Activity 1) and the existing OCAP CO_2 network supplying greenhouses. It is hoped that the hub will be the starting point for large-scale CCS in the region, connecting all large CO_2 point sources in the Rotterdam area, as well as also benefiting more distant CO_2 point sources, including Antwerp and Germany. There are also options for CCU applications to be developed, including the supply of CO_2 for enhanced oil recovery (EOR). The Port of Rotterdam is currently working on a concrete plan for CCS from industrial sources, with an initial connection to at least 1 industrial source to launch the pipeline.

UK East Coast CCS cluster

A UK East Coast CCS cluster will link up existing industrial hubs with transport and storage infrastructure in the North Sea Basin. Industrial operators in the Tees Valley region of North East England have come together to design and propose a CCS cluster that allows multiple sources of CO_2 to use a common transport and storage infrastructure. Following a feasibility study an early phase project is proposed, which would capture and store 11 million tonnes of CO_2 over 15 years. This network could then be expanded to capture 10 million tonnes of CO_2 per year as power stations and further industrial companies join the network.

Le Havre CCS cluster

The Le Havre Harbour area emits around 10 $MtCO_2$/year. A European FP7 project - COCATE - aimed to evaluate the cost of capture and clustering the CO_2 emissions for pipeline and ship transport towards the Rotterdam area and the North Sea. Since then several projects on CO_2 capture and hydrogen have been deployed in the territory.

Fos-Berre/Marseille CCU cluster (Flagship Project)

The Fos-Berre/Marseille CCU cluster gathers industries and public sector (GPMM i.e. Port Authority). In the near future, an important infrastructure component (pipeline collecting CO2 from different sources and feeding different applications) will be set up. The main benefits for the territory is maintaining industries and reducing their CO2 emissions in the same time by developing a circular approach (industrial symbiosis). The Fos-Berre/Marseille CCU cluster supports a wide range of CCU technologies from chemicals and biological transformation to produce chemicals, material and fuels.

Feasibility for a European hydrogen infrastructure

A European hydrogen infrastructure, combining CCS and hydrogen produced either through the pre-combustion processing of hydrocarbons through Steam Methane Reforming (SMR) or electrolysis using renewable energy, could create options to replace the use of fossil fuels for transport, industry, heating, and cooking applications. This production would take place in large-scale plants and be distributed through existing infrastructure serving natural gas applications. There is also the option to use hydrogen generated from electrolysis, along with captured CO_2 to produce fuels and chemicals, such as methanol, linking to actions identified under R&I Activity 7 (CCU Action).

The CO_2 emissions generated from the hydrogen production process via the SMR route can be captured (by pre-combustion capture technologies) and stored. This also provides opportunities to limit emissions from many small emission sources where CO_2 capture is impractical. There are no technical barriers to large-scale hydrogen production; however, further assessment is needed to improve the understanding of the possibilities and limitations (including potential safety aspects) of using existing infrastructure for the transport and use of hydrogen-enriched natural gas. Also important will be understanding the possible environmental and climate related benefits and trade-offs where hydrogen replaces fossil fuels, including an assessment of the sustainability and CO_2 abatement potential for the various hydrogen production options and uses. In addition, process intensification, process integration and emerging new capture technologies should be investigated to obtain more efficient and economic solutions for hydrogen production.

Identification of gaps

The Norwegian CCS cluster is making good progress, with a FEED study currently underway. However, the remaining clusters proposed are currently at differing stages of development. In order to realise the 2030 Declaration of Intent KPI - to have a minimum of 5 commercial-scale CCS projects in the CO_2 emission intensive industries - then progress on further CCS and CCU clusters is required. By 2020 the remaining 4 clusters should aim to have completed pre-FEED studies, in addition to completed concept development and cost studies.

At present the CCS and CCU clusters being progressed are concentrated in Western Europe, with a particular focus around the North Sea Basin. To achieve greater geographical distribution of CCS and CCU clusters within Europe, feasibility studies should consider options in Eastern European regions. This could involve onshore or offshore storage of CO_2, and could further benefit from a separate ship transportation feasibility study, building on work in this area by Norway and the UK[8]. This may provide a route for the cross-border transport of CO_2 from additional industrial CCS and CCU clusters to storage sites where indigenous storage is not available. To enable this, 2-3 additional feasibility studies, should be initiated by 2020. These studies may proceed alongside proposed actions under Activities 4 and 5 (Establish a European CO_2 Storage Atlas and CO_2 storage pilots in operation), also benefiting from the proposed ship transportation feasibility study.

[8] Feasibility assessment of the options for up-scaling proposed CCS facility (National Grid Carbon, Det Norske Veritas (DNV), 2015)

Pathway to 2030 and beyond

Realising the 2030 Declaration of Intent KPI target to have a minimum of 5 commercial-scale CCS projects in the CO_2 emission intensive industries and 10 projects in the power sector requires the delivery of the 5 CCS clusters already being progressed, with all projects at least reaching the FEED study and then construction stage in the early to mid-2020s. In addition, a further 2 to 3 additional CCS and CCU clusters should be initiated, preferably located in Eastern Europe.

Table 2a: DOI Targets and Monitoring Mechanisms

DOI Target	Monitoring mechanism
Target 2: At least one commercial scale CCS project linked to an industrial CO_2 source, having completed a FEED study	*Norwegian CCS cluster:* • Completion of FEED study on Norwegian CCS cluster by 2019
Target 3: SET Plan countries having completed, if appropriate in regional cooperation with other MS, feasibility studies on applying CCS to a set of clusters of major industrial and other CO2 sources by 2025-2030, if applicable involving cooperation across borders for transporting and storing CO2 (at least 5 clusters in different regions of the EU)	*Rotterdam, UK East Coast, Le Havre, and Fos-Berre/Marseille CCS and CCU clusters:* • Rotterdam CCS and CCU cluster completed feasibility and FEED studies by 2020 (with the expectation to be operational in 2020/21) [ongoing] • UK East Coast CCS cluster completed feasibility study and ready to begin FEED study by 2020 [ongoing]. • Le Havre CCS cluster completed feasibility study and ready to progress with FEED study by 2020 [ongoing] • Fos-Berre/Marseille CCU cluster completed feasibility study and ready to progress with FEED study by 2020 [ongoing] *Feasibility studies for further industrial CCS and CCU clusters* • To achieve geographical balance of CCS and CCU clusters feasibility studies for 2-3 regions, including onshore and offshore storage options or ship transport, have been completed, with at least 1 progressing to pre-FEED stage beyond 2020 *Feasibility for a European hydrogen infrastructure* • Study undertaken into the feasibility of a European hydrogen infrastructure • Inclusion of feasibility for a hydrogen infrastructure topic in the Horizon 2020 2018/19 Energy Work Programme
Target 10: By 2020, Member States having delivered as part of the Energy Union Governance their integrated national energy and climate plans for after 2020, and having identified the needs to modernise their energy system including, if applicable, the need to apply CCS to fossil fuel power plants and/or energy and carbon	*Norwegian, Rotterdam, UK East Coast, Le Havre, and Fos-Berre/Marseille CCS and CCU clusters:* • Assesment of the socio-economic benefits of CCS and CCU clusters undertaken *Feasibility for a European hydrogen infrastructure*

intensive industries in order to make their energy systems compatible with the 2050 long-term emission targets	• Assessment of the sustainability and CO_2 abatement potential for the various hydrogen production options and uses
Pathway to 2030 and beyond	**Monitoring mechanism**
5 commercial-scale CCS projects in the CO_2 emission intensive industries	*Norwegian, Rotterdam, UK East Coast, Le Havre, and Fos-Berre/Marseille CCS and CCU clusters:* • Norwegian CCS cluster operational by 2022 • Multiple CCS and CCU clusters moving into FEED and construction in the early to mid-2020s. • Completed ship transport feasibility study, building on previous work done by Norway and the UK, which can provide options for feasibility studies of industrial CCS and CCU clusters in regions without access to CO_2 storage resources. *Feasibility studies for further industrial CCS and CCU clusters* • Having completed feasibility studies the most promising CCS and CCU clusters have been progress to pre-FEED stage. *Feasibility for a European hydrogen infrastructure* • One or more early hydrogen infrastructure projects being developed

Expected deliverables and timeline

Norwegian CCS cluster:

- Completion of FEED study for Norwegian industrial CCS cluster in **2019** (with the aim to be operational by **2022)** [ongoing].

Progression of Rotterdam, UK East Coast, Le Havre, and Fos-Berre/Marseille CCS and CCU clusters:
In order to meet Target 3, a further 4 of the industrial CCS and CCU clusters need to have at least reached pre-FEED stage, and be ready to begin FEED studies:

- By **2020**, all 5 industrial CCS and CCU clusters have completed pre-FEED studies and are ready to progress to FEED stage.

Feasibility for further industrial CCS and CCU clusters:
A further 2 to 3 regions with the potential to develop industrial CCS and CCU clusters need to be identified and advanced for feasibility studies, with consideration of geographical balance. Selection of additional industrial CCS and CCU clusters should attempt to achieve a greater geographical distribution of CCS and CCU projects, beyond the North Sea Basin. The feasibility and FEED studies, as well as the implementation of the clusters, will require support from Member States, industry and the European Commission, with funding through the Innovation Fund [proposed].

- Feasibility studies completed for 2 to 3 additional industrial CCS and CCU clusters by **2020** [proposed]

Feasibility for a European hydrogen infrastructure:

The sustainability and CO_2 abatement potential offered by the replacement of fossil-based hydrogen production options should be included within European and national energy and climate plans (see R&I Activity 8), towards achieving Target 10.

- Study undertaken into the feasibility of a European hydrogen infrastructure by **2020** [proposed].
- Assessment of the sustainability and CO_2 abatement potential for the various hydrogen production options and uses by **2020** [proposed].
- Evaluation of potential for hydrogen to reduce CO_2 emissions in the transport, heating, industrial and power sectors as part of national and international energy and climate plans by **2020** [proposed].

Table 2b: Financing of planned activities to 2020

Parties	**Implementation Instruments**	**Indicative financing contribution**
Norwegian CCS cluster:		
Norwegian Government, Norcem AS, Yara Norge AS, Waste-to-Energy Agency in Oslo municipality, Gassco, Statoil.	State funding and private funding.	€800-1400 million of expected planning and investment costs, depending on how many sources from which CO_2 will be captured. Status: Under development. Estimates based on feasibility study. *STATUS: confirmed*
Rotterdam CCS and CCU cluster:		
Port of Rotterdam Authority, Relevant companies in Rotterdam Harbour Area (including: TAQA, Maasvlakte CCS project, OCAP/Linde Gas, and more)	Public / private funding	Total estimated costs €235 million for realisation of the backbone pipeline in the Rotterdam port area (connecting Maasvlakte with OCAP), 43 Mton storage field and 500kton CO_2/yr next to ROAD project). *STATUS: proposed*
Netherlands Government	Roadmap for CCS in the Netherlands, to be developed in 2017, will include suitable instrumentation.	
UK North East CCS and CCU cluster:		
Teesside Collective, Tees Valley Combined Authority, UK Government	Proposed funding mechanism using state and private funds.	£110 million to capture CO_2 from three sites, and £16 million per year operational cost, amounting to 730,000 tonnes a year. An additional £340 million capex and £26million opex to capture CO2 from three additional sites bringing the total CO2 to 2,430,000 tonnes per year. £71 million to run a 17 km 15 million tonne capacity

		onshore pipe through Teesside connecting sites, and £252 million to run a 154 km 15 million tonne capacity pipe to Endurance, with an £11 million per year operational cost for the on and offshore pipe network. *STATUS: proposed*
Le Havre CCS cluster:		
Le Havre Development and relevant companies in Le Havre Harbour Area	Private and state funding	Cost not yet determined *STATUS: proposed*
Fos-Berre/Marseille CCU cluster		
Stakeholders include GPMM, INOVERTIS, IFREMER, COLDEP, ArcelorMittal, Solamat Merex, Kem One, CEA, San Ouest Provence	Private and state funding	Cost not yet determined *STATUS: proposed*
Feasibility studies for further industrial CCS and CCU clusters:		
European Commission and National governments	Horizon 2020 2018/19 Energy Work Programme Innovation Fund (planned under a reformed Emission Trading System/ETS) State funding	CCS and CCU projects will be eligible for funding under a future EU ETS Innovation Fund; detailed rules for this fund are currently being developed. It is expected that a further 2-3 feasibility studies for future European CCS and CCU clusters would cost €2-3 million. *STATUS: proposed*
Feasibility for European hydrogen infrastructure		
Governmental CCS and CCU bodies, industry, both vendors and users, engineering companies, research organisations, academia, European Commission and Member States	Providing options for CCS and CCU clusters to develop hydrogen infrastructure will require support from the European Commission and a dedicated topic under the Horizon 2020 Energy Work Programme for 2018/19.	Costs to be determined for R&D and pre-feasibility studies for future hydrogen infrastructure. *STATUS: proposed*
EERA CCUS to Contribute towards R&D actions		
		Total budget required: to be determined

Table 2c: Financing of planned activities to 2030

Parties	**Implementation Instruments**	**Indicative financing contribution**
Feasibility studies for further industrial CCS clusters including ship transport feasibility study		
Industrial CCS and CCU	Innovation Fund (planned under	CCS and CCU projects will be

clusters: European Commission, Member States, and private sector	a reformed Emission Trading System/ETS)	eligible for funding under a future EU ETS Innovation Fund; detailed rules for this fund are currently being developed. It is expected that a further 2-3 feasibility studies for future European CCS and CCU clusters would cost €2-3 million. *STATUS: proposed*
Ship transport feasbility study: European Commission and Member States	Build on previous studies within Cintra, CATO-Climit etc.	Costs to be determined for a ship transport feasibility study to allow for cross-border transport of CO_2 and providing options to develop additional industrial CCS and CCU clusters in regions of Europe without access to storage resources. *STATUS: proposed*
Feasibility for European hydrogen infrastructure		
Governmental CCS and CCU bodies, industry, both vendors and users, engineering companies, research organisations, academia, European Commission and Member States	European Commission funding, and support through future R&D strategies under Framework Programme 9 State funding	Costs for the development of one or more early hydrogen infrastructure projects will be dependent on outcomes of initial feasibility studies *STATUS: proposed*
		Total budget required: to be determined

R&I Activity 3: EU Projects of Common Interest (PCI) for CO_2 transport infrastructure

Responds to ***Target 4****: At least 1 active EU Project of Common Interest (PCI) for CO_2 transport infrastructure, for example related to storage in the North Sea* and ***Target 3****: SET Plan countries having completed, if appropriate in regional cooperation with other MS, feasibility studies on applying CCS to a set of clusters of major industrial and other CO_2 sources by 2025-2030, if applicable involving cooperation across borders for transporting and storing CO_2 (at least 5 clusters in different regions of the EU)*

Overview of existing and planned activities

Progression of at least 1 EU Project of Common Interest

Reaching long-term European climate targets requires wide CCS deployment. In the second half of this century, the magnitude of CO_2 stored should be in the order of hundreds of million tonnes CO_2 annually. This will require a large pan-European CO_2 transport infrastructure that links CO_2 sources and sinks in a cost effective way, as well as feeding CCU applications. In order to ensure that the CO_2 transport infrastructure is available in due time planning needs to start before 2020. In some instances the timely re-purposing of existing petroleum infrastructure may achieve cost reductions for first-of-a-kind projects, particularly where this re-purposing can be achieved rapidly. The potential cost-benefits and opportunity windows need to be well understood, in addition to actions which may be required to preserve strategically important infrastructure at risk of decommissioning and removal.

The European Commission has established an instrument to accelerate infrastructure development called Projects of Common Interest (PCI). The ambition is that PCIs should contribute to complete the European internal energy market and to reach the EU's energy policy objectives of affordable, secure and sustainable energy. PCIs can apply for financial support through the Connecting Europe Facility (CEF), with the most recent opportunity for PCI selection being early-2017, with such funding intended to accelerate the projects and attract private investors.

The PCI instrument could be the starting point for pan-European CO_2 transport infrastructure. Actions must start already in 2017 to ensure that a new PCI on CO_2 transport infrastructure can be established. The process for applications for PCI status and access to Connecting Europe Facility (CEF) is currently underway and the European Commission has announced that 4 projects have put in applications, with the successful project/s expected to be announced in mid-2017.

The proposed UK CO_2 Sapling CCS project will initiate a low cost full chain CCS project in the North East of Scotland. This will act as a seed for a cluster of capture, transport and storage infrastructure which will contribute significantly to the commercial decarbonisation of the region. Infrastructure can be further developed by adding additional CO_2 capture points, such as from hydrogen manufacture for transport and heat, future CO_2 shipping through Peterhead Port to and from Europe, and connection to UK national onshore transport infrastructure such as the FEEDER 10 pipeline which can bring additional CO_2 from emissions sites in the industrial central belt of Scotland including the proposed Caledonia Clean Energy Project.

The Rotterdam Nucleus is an PCI proposal initiative led by the Port of Rotterdam Authority, accompanied by a number of industrial stakeholders, and supported by research institute TNO. The PCI proposes a modular CO_2 transport infrastructure that connects the Rotterdam harbour to storage reservoirs in the Dutch and UK sections of the North Sea. At full-scale, this PCI has the potential to decarbonise large portions of industrial emissions from the Rotterdam harbour, but also from the ports and Antwerp in Belgium, and the industrial region of North Rhine Westphalia in Germany. This PCI has also been designed to reduce the capital and operational costs needed, as it has the potential to unlock stranded gas reserves in the North Sea, with part of the value derived from gas exploitation being used to offset the PCI infrastructure investment costs.

In addition Statoil ASA and Tees Valley Combined Authority have both submitted projects, with the former linking emissions sources in the Teesside Industrial Cluster with the Eemshaven area in the Netherlands and a storage site on the Norwegian Continental Shelf.

The North Sea Basin Task Force (NSBTF) has developed the "North Sea Strategic Regional Plan", with the primary purpose of assisting bids for PCI projects. The NSBTF is composed of public and private bodies from countries around the perimeter of the North Sea. The NSBTF recognises that the North Sea Basin is the most logical place in Europe to start transport and storage of CO_2 and that the countries bordering the North Sea need to coordinate and plan together to deliver an optimum network. North Sea Basin Task Force also encourages collaboration between PCIs. An example is the ongoing Norwegian CCS initiative (an expected deliverable under R&I Activity 2), which aims to build storage capacity, in excess of the need for storage volumes in the current project. Additionally, Statoil has submitted an application for PCI on the concept of CO_2 transport from point sources in the UK and the Continent to the storage site on the Norwegian Continental Shelf by ship.

The Horizon 2020 funded Gateway project is a first step towards deployment of CCS through a cross-border CO_2 transport infrastructure, providing a strategic decision basis to enable all stakeholders to identify and implement measures that can accelerate deployment of technologies needed for realisation of large-scale CCS projects based on European CO_2 transport infrastructure. It is expected that one PCI submitted will build on recommendations established by the Gateway project.

Identification of gaps

The London Protocol prohibits the export of CO_2 from a contracting party to other countries for injection into sub-seabed geological formations. The protocol was amended in 2009 to enable cross-border CCS projects, but the amendment must be ratified by two-thirds of contracting parties to enter into force. Given the required number of ratifications and difficulties associated with the ratification process, it appears unlikely that two-thirds of contracting parties will be in a position to ratify the amendment in the near term. Raising awareness among relevant government ministries of the importance to global CCS deployment of ratifying the London Protocol amendment should be a priority. Consideration should be given to options identified by the International Energy Agency[9] that may be available to contracting parties under international law to address this barrier to CCS deployment pending formal entry into force of the 2009 amendment.

Pathway to 2030 and beyond

At least one of the projects awarded PCI status in the current application round takes a positive investment decision and is constructed. This project will be an enabler for subsequent projects by testing the regulatory and legal framework, and successfully navigating any potential issues which arise. The development of cross-border CCS projects can be enablers for projects in countries without access to indigenous CO_2 storage resources thereby broadening the range of countries that can benefit from the development of CCS.

Table 3a: DOI Targets and Monitoring Mechanisms

DOI Target	**Monitoring mechanism**
Target 4: At least 1 active Project of Common European Interest for CO_2 transport infrastructure, for example related to storage in	• At least 1 of the 4 projects which submitted an application awarded PCI status in 2017 application round

[9] Carbon Capture and Storage and the London Protocol (IEA, 2011)

the North Sea.	• Delivery of the Gateway project in 2017 providing a comprehensive integrated PCI project proposal providing a model for establishing European CO_2 infrastructure • Successful PCI project/s have access to funding through the Connecting Europe Facility in 2018 • Continuation of NSBTF work to building collaboration between PCI projects
Target 3: SET Plan countries having completed, if appropriate in regional cooperation with other MS, feasibility studies on applying CCS to a set of clusters of major industrial and other CO_2 sources by 2025-2030, if applicable involving cooperation across borders for transporting and storing CO_2 (at least 5 clusters in different regions of the EU)	• At least 1 of the 4 projects which submitted an application awarded PCI status in 2017 application round
Pathway to 2030 and beyond	**Monitoring mechanism**
At least 1 PCI project from 2017 application round undertakes FID and is developed Further projects apply for PCI status under 2019 call for applications	• Application of further PCI projects as part of 2019 call for applications for PCI status. • Projects in regions without CO_2 storage options enabled through ship transport feasibility study, identified under R&I Activity 2.

Expected deliverables and timeline

Progression of at least 1 European Project of Common Interest

Project promoters from The Netherlands, UK, and Norway have already taken a key role to establish the PCIs. Other MS and associated countries close to the North Sea should also engage in this work. NSBTF will also play a key role. Other MS should engage to identify the possibilities for PCIs in other areas than the North Sea. Continuation of the ongoing support from European Commission will be essential.

- At least 1 of the 4 projects submitted to the 2017 application call on CO_2 transport infrastructure is awarded PCI status, in **2017** and access ensuring to funding through the CEF mechanism by **2018** [ongoing].
- Further applications for PCI projects under **2019** call [proposed].

Table 3b: Financing of planned activities to 2020

Parties	Implementation Instruments	Indicative financing contribution
Progression of at least 1 European Project of Common Interest		
Dutch Government UK Government Norwegian Government Belgian Government German Government	National Government programmes and funds	Not yet determined *STATUS: proposed*
Statoil ASA Port of Rotterdam Authority	Project promoters	Not yet determined

Tees Valley Combined Authority Pale Blue Dot		*STATUS: proposed*
European Commission	Connecting Europe Facility Horizon 2020 2018/19 Energy Work Programme	*STATUS: confirmed*
EERA CCS to contribute on *R&D Actions*		
Gateway Project		
European Commission	Horizon 2020	€787,000 *STATUS: confirmed*
		Total budget required: To be determined

Table 3c: Financing of planned activities to 2030

Parties	**Implementation Instruments**	**Indicative financing contribution**
Development of at least 1 of the European Project of Common Interest awarded funding under the 2017 call		
Dutch Government UK Government Norwegian Government	National Government programmes and funds	*STATUS: proposed*
European Commission	Connecting Europe Facility Support through future R&D strategies under Framework Programme 9	*STATUS: proposed*
EERA CCS	Contribution on *R&D Actions*	
Progression of European Projects of Common Interest under the 2019 funding call		
National Governments and Industry	National Government programmes and funds	*STATUS: proposed*
European Commission	Connecting Europe Facility Horizon 2020 2018/19 Energy Work Programme	*STATUS: proposed*
EERA CCUS to Contribute towards R&D actions		
		Total budget required: To be determined

R&I Activity 4: Establish a European CO_2 Storage Atlas

Responds to ***Target 5:*** *An up-to-date and detailed inventory of the most suitable and cost-effective geological storage capacity (based on agreed methodology), identified and accepted by various national authorities in Europe*

Overview of existing and planned activities

A European CO_2 Storage Atlas identifying and characterising all recognised prospective storage sites on a consistent basis is needed to facilitate site comparison, site ranking, and integrated regional or national planning of storage and transport development. The atlas will greatly assist project developers and relevant permitting authorities to prioritise the most prospective areas for both onshore and offshore CO_2 storage, and will enable the design and development of transport infrastructure to be optimised.

Several assessments of European CO_2 storage have been made, the most recent version being the CO_2 storage atlas. This atlas is to be released in 2018 via EC JRC and will be embedded in the EuroGeoSurveys[10] European Geological Data Infrastructure (EGDI). However, although this atlas builds on preceding projects such as EU GeoCapacity and particularly CO_2 SToP, it has been superseded in certain European countries which have completed significantly more detailed assessments and databases of their storage resources.

An updated European CO_2 Storage Atlas will create and adopt, as appropriate, best practice which might include the Storage Resource Management System being developed by the Society of Petroleum Engineers, building on existing storage assessments, which can include the Norwegian Petroleum Directorate Storage Atlas published in 2014, the Nordic CO_2 Storage Atlas published in 2015, and the Strategic UK CO_2 Storage Appraisal Project (CO_2 Stored) published in 2016. The aim will be to develop consistent and comparable estimates of European storage capacity to enable site selection for further detailed appraisal and strategic planning of transport and storage infrastructure.

A European CO_2 Storage Atlas will be the foundation from which a strategic portfolio of 'bankable' stores can be developed. It will not however, provide this portfolio by itself as each store will require more detailed project-specific characterisation, appraisal, design and permitting, such as through the actions outlined under R&I Activity 5. However, these storage appraisal activities may further validate storage assessments in different geological settings within the European CO_2 Storage Atlas.

Identified gaps

Initiating work programmes to establish a CO_2 storage atlas, comparing advanced work in this area, such as that completed by the UK and Norway in order to ensure an agreed set of methodologies is adopted. In order to maximise the value of early efforts this should focus on regions identified under R&I Activity 2 of the Implementation Plan. Later efforts should focus on developing a wider storage atlas to facilitate CCS across Europe. In addition, a European body needs to be needs to be identified which can host the Atlas and facilitate its regular updating. This should link to the infrastructure requirements identified under R&I Activity 5, including those offshore.

Pathway to 2030 and beyond

A process will be put in place to ensure that the Atlas is reviewed and updated, this should also link to delivery of the storage pilot projects outlined in R&I Activity 5.

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[10] http://www.eurogeosurveys.org/

Continued development is needed to expand the initial storage atlas towards a comprehensive Europe-wide atlas, with periodic reviews of the approach to ensure best-practice. Further evaluation is needed to determine how the CO_2 storage atlas can be expanded, and mapping continued, in regions without existing data or funding available.

Table 4a: DOI Targets and Monitoring Mechanisms

DOI Target	**Monitoring mechanism**
Target 5: An up-to-date and detailed inventory of the most suitable and cost-effective geological storage capacity (based on agreed methodology), identified and accepted by various national authorities in Europe	• Agreement on a staged methodology for the determination of storage capacity at different levels of detail • Agreement on, and implementation of, an organisational structure • Completion of Storage Resource Management System, currently being developed by the Society of Petroleum Engineers, and study undertaken to contract with existing UK approaches. • Delivery of a CO_2 storage atlas based on an agreed set of methodologies for member states and regions to meet CCS policies and plans, including the expected CO_2 supply from clusters of emitters. • Methodologies to consistently evaluate storage capacities will be defined, including risk and liability assessments and techno-economic assessments, in addition to geological assessments. • Identification of an existing, or create a new pan-European body to collect and coordinate storage information on a regular basis.
Pathway to 2030 and beyond	**Monitoring mechanism**
Expansion of European Storage Atlas	• Identification and inclusion of storage resources beyond the initial study of regions identified in R&I Activity 2.

Expected deliverables and timeline

The establishment of a European **CO_2** Storage Atlas will deliver the following:

- Agreement and implementation of an organisational structure by **2018** [proposed].
- Collation of National storage assessments to produce a European CO_2 Storage Atlas, to be completed and released in **2020**.
- Collation of national storage assessments to produce an updated European Storage Atlas based on an agreed set of methodologies for member states and regions to meet CCS policies and plans, including the expected CO_2 supply from clusters of emitters to be completed and released in **2020** [proposed].
- Release of European CO_2 storage atlas in **2018**
- Fit-for-purpose (i.e. matched to potential CO_2 capture rates) estimates of storage capacities, based on simulations of credible capture, transport and injection scenarios. Agreement on a set of methodologies for storage capacity determination in **2018**.
- An online, freely accessible, decision support system (webGIS) that allows potential site developers to obtain basic geological information on potential sites.

- Support of appraisal activities carried out as part of R&I Activity 5.

Table 4b: Financing of planned activities to 2020

Parties	**Implementation Instruments**	**Indicative financing contribution**
Establish an updated European CO_2 Storage Atlas		
Collaboration between EuroGeoSurveys, ENOS project Consortium, CO_2GeoNet, JRC-European Commission, ENeRG with support from the European Commission, Norwegian, UK Dutch, and German Governments, Statoil, and CCS project consortia throughout Europe.	State funding Industry funding Horizon 2020 2018/19 Work Programme	Up to €10 million needed for further appraisal in selected regions and completion of the atlas and additional funding for future updates and online operations of the atlas. *STATUS: proposed*
NSBTF- process will join up the existing storage assessments for the North Sea region.		*STATUS: confirmed*
Other existing or recent activities and National storage studies which could be incorporated into a storage atlas, subject to procedures to ensure consistent reporting of estimations:		
Limited work on storage capacity methodology and determination ongoing in H2020 ENOS project (WP2)	European Commission through Horizon 2020	€12.4 million STATUS: confirmed
Norwegian Petroleum Directorate Storage Atlas- database was published in 2014 and provides ongoing information for future exploration for CO_2 storage sites. [completed]	State funding	*STATUS: confirmed*
Building Nordic Excellence In CCS (NORDICCS – The Nordic CCS Competence Centre, published interactive storage atlas and report in 2016.	State funding	€1.2 million Funded by Top Level Research Initiative (TRI)/ Nordic Innovation *STATUS: confirmed*
Strategic UK CO_2 Storage Appraisal Project- database was published in 2016 and is publically available, providing an ongoing resource to inform decisions on the economics of storage opportunities.	State funding	£4 million spent on the Strategic UK CO_2 Storage Appraisal Project. Detailed appraisal of 5 stores from a portfolio of 20 'high-ranked' potential sites in the UK was achieved with a further £1 million. *STATUS: confirmed*
Speicherkataster Storage Catalogue of Germany-	State funding	Speicherkataster Storage Catalogue of Germany- €1.067

published open access in 2011		million state funding; €0.3 million private funding *STATUS: confirmed*
Netherlands CO_2 Transport and Storage Plan	State funding	Netherlands CO_2 Transport and Storage Plan will be funded by the Dutch Government *STATUS: confirmed*
FENCO Utsira Aquifer (Germany) Analysis of potentials and costs of CO_2 storage in the Utsira aquifer in the North Sea	State funding	€ 0.178 million State spent on FENCO Utsira Aquifer (Germany) Analysis *STATUS: confirmed*
EuGeoCapacity, CASTOR, GESTCO, Joule II, CO_2StoP.	State funding	Estimated € 6-7 million from FP6 and FP7 spent *STATUS: confirmed*
BASRECCS CO_2 storage assessment in the Baltic region	State funding	> €0.05 million *STATUS: confirmed*
		Total budget required: €10 million to establish CO_2 storage atlas in selected regions

Table 4c: Financing of planned activities to 2030

Parties	Implementation Instruments	Indicative financing contribution
Expansion and updates of European CO_2 Storage Atlas		
EuroGeoSurveys, ENOS project Consortium, CO2GeoNet, JRC-European Commission, ENeRG with support from the European Commission, Norwegian, UK Dutch, and German Governments, Statoil, and CCS project consortia throughout Europe.	State funding Industry funding European Commission funding and support through future R&D strategies under Framework Programme 9	Cost to expand/maintain around €10 million
		Total budget required: €10 million to expand and maintain CO_2 storage atlas

R&I Activity 5: Unlocking European Storage Capacity

Responds to ***Target 7:*** *At least 3 new CO_2 storage pilots in preparation or operating in different settings*, ***Target 2***: *At least one commercial scale CCS project linked to an industrial CO_2 source, having completed a FEED study,* and ***Target 3:*** *SET Plan countries having completed, if appropriate in regional cooperation with other MS, feasibility studies on applying CCS to a set of clusters of major industrial and other CO_2 sources by 2025-2030, if applicable involving cooperation across borders for transporting and storing CO_2 (at least 5 clusters in different regions of the EU)*

Overview of existing and planned activities

Work has already been undertaken to produce a comprehensive CO_2 storage atlas that can facilitate the future development of CO_2 storage sites (see R&I activity 4, creation of a European CO_2 Storage Atlas). Initial projects, planned under R&I activities 1 to 3, can be used to support the validation of the storage potential undertaken as part of R&I Activity 4. However, in order to store meaningful quantities of CO_2 to attain targets under the Paris Agreement, new storage sites will need to be characterised and appraised every year for the next 30 years. The storage atlas will help identification of potential storage locations to be evaluated. In parallel all SET-Plan countries should establish national transport and storage plans and by aligning these national plans it will be possible to identify CO_2 storage projects that could be established as joint European CO_2 storage projects on the basis of their importance to European CCS development.

The principle of a pilot is to prepare the way for subsequent larger scale activity. The benefit of a pilot is to demonstrate storage technology/ies to the public as a safe and effective technology or to appraise the suitability of a storage location. The impact of a series of pilots will be to increase the confidence of all stakeholders in CCS and the associated technologies. The first appraisal steps are likely to start offshore in the North Sea region. In later stages – building on the experience with offshore storage – storage can unfold onshore provided that the local public is supporting the safety and effectiveness of this mitigation technology. In this respect small-scale storage projects can play a crucial role in visualizing the technology to the public.

Actions under this R&I Activity will build on a number of ongoing and completed projects. This includes a study by Pale Blue Dot Energy in 2015 to deliver an open access screened and appraised portfolio of offshore geological CO_2 storage sites. The project for the then UK Department for Energy and Climate Change and the Energy Technologies Institute involved a detailed appraisal of five CO_2 storage sites, facilities concept design and costing and economics.[11] The H2020 project is developing a portfolio of onshore storage pilots which will be available by 2018. Follow on pilots to demonstrate and appraise these sites and prospective sites resulting from R&I Activity 4 would be examples for this R&I Activity 5.

To contribute to target 7, the new storage pilots should confirm with the criteria listed below;

- Demonstration or evaluation of monitoring and verification techniques, and/or techniques for improving the storage performance (e.g. pressure management) for CO_2 storage or CO_2 EOR (onshore or offshore)
- Permeability, injectivity, pressure gradient and storage boundary tests by producing or injecting (not necessarily CO_2) fluid from or into target storage layers (onshore or offshore wells)
- Pilot CO_2 storage sites with cumulative injection of 100,000 tCO_2. Such pilots do not require a storage license and will test technology to be applied elsewhere and/or investigate

[11] https://pale-blu.com/track-record/track-record-ccus/

characteristics of specific subsurface layers (for example consider these pilots to be conducted onshore at relatively low cost to be extrapolated to large scale stores offshore)
- Where substantial investment (e.g. over 50 million €) is involved, it is recommended that the CO_2 storage pilot infrastructure should complement subsequent large-scale CO_2 storage offshore or even CO_2 EOR onshore (for example at the Czech LBr1 site), which includes synergies with R&I Activities 1 to 4.
- Re-assurance of storage technology as a safe and effective climate mitigation measure in different onshore industrial settings by visualisation to the public and their participative involvement.

A number of small-scale storage pilots in different lifetime stages which may conform to these criteria are included in the project annex. This R&I Activity is directed to the development of new storage pilots which have not yet reached the construction stage.

Identified gaps

An assessment of these existing and proposed new storage pilots is required to identify those which can deliver on the criteria outlined above. If none of the new storage pilots listed in the project annex are able to deliver the actions required under Target 7 new storage pilots need to be identified and progressed, helped by using existing national and European storage atlases to identify high-ranking locations, sites, and storage layers and other evaluations for the on- and off-shore.

The development of the storage pilots should be actively promoted to find financial support from public and private entities.

Pathway to 2030 and beyond

In order to achieve the targets set out in the Declaration of Intent KPIs 15 Permits for storage pilots need to have been granted or are in an advanced stage of permitting by 2030. A process needs to be put in place by which information from small-scale storage projects may feed back into large-scale storage assessments and the European CO_2 Storage Atlas produced as part of actions under R&I Activity 4 of the Implementation Plan.

Accelerating CCS Technology (ACT) is a European initiative to establish CO_2 capture and storage as a tool to combat global warming. Currently, the initiative has ten funding partner countries in Europe. Its ambition is to fund research and innovation projects that can lead to safe and cost effective technology. With a total budget of €41 million from nine partner countries, ACT has recently completed an open call for proposals, with the aim to launch eight new ACT-supported projects in August 2017. Projects emerging from ACT could produce results that can pave way for large-scale storage in Europe. The ACT initiative is planning to announce new calls in 2018 and 2020.

Further development of CO_2 storage technologies to 2030 and beyond will require availability of world class R&D infrastructure. The ESFRI project ECCSEL has recently been established as a European Research Infrastructure Consortium (ERIC) and has an ambition to become a key R&D instrument to meet the objectives of the SET Plan. ECCSEL ERIC offers state-of-the-art R&D infrastructure related to CCS and aims at building and operating R&D infrastructure that can be accessed by researchers all over Europe, who are welcome to apply to use the infrastructure. The synergies between ECCSEL ERIC and ambitious R&D activities will be essential in developing safe and cost effective solutions for CO_2 storage. ECCSEL ERIC will interact with relevant bodies, such as EERA, ETIP ZEP and others in order to ensure that ambitious R&D activities benefit from world class R&D infrastructure. ECCSEL ERIC aims to facilitate projects in the European Commission's Framework Programmes, future European industrial initiatives and education of specialists for the new CCS industry.

Table 5a: DOI Targets and Monitoring Mechanisms

DOI Target	Monitoring mechanism
Target 7: At least 3 new CO2 storage pilots in preparation or operating in different settings	• Portfolio of identified opportunities with the use suitable pilots in the Project Annex and evaluations from ENOS in 2018 and Pale Blue Dot in 2015 • Funding awards and projects commissioned • Designs completed for small-sale storage pilots covering range of geological and geographical contexts. • At least 3 small-scale storage pilots commissioned.
Pathway to 2030 and beyond	**Monitoring mechanism**
15 permits for CO_2 storage in Europe	• Delivery of the most promising CO_2 storage pilots projects from the CO_2 storage atlas (R&I Activity 4) will be progressed, but additional projects will need to be identified and developed every year.

Deliverables and timeline

Parties most appropriate to deliver small-scale storage pilots and projects would be potential CO_2 storage project developers (oil and gas companies and associated engineering firms or public-private consortia) working closely with the CO_2 storage research community. This will deliver the following outcomes:

- Expand European experience of CO_2 storage across a range of storage options and industrial regions
- Development of at least 3 storage pilots, covering a range of storage options by **2020** [ongoing]
- Identification and appraisal plans for the most promising storage sites identified in the European CO_2 Storage Atlas (R&I Activity 4) by **2020** [ongoing]
- Improved understanding of monitoring and verification, and how to conform to the requirements of the CCS Directive in a cost-effective way by **2020** [ongoing].
- Commissioning of at least one CO_2 storage pilot by **2020**

Table 5b: Financing of planned activities to 2020

Parties	Implementation Instruments	Indicative financing contribution
Advancing 3 storage projects		
National Governments Industry European Commission	State funding Innovation Fund Norway Grants 2014-2021	Costs for small-scale storage pilots expected to be between €10-50 million for construction onshore (increased where construction is offshore), excluding CO_2 supply (if needed).

		STATUS: proposed
ZEP and EERA	Coordination and promoting	
EERA CCUS to Contribute towards R&D actions		
		Total budget required: €10-150 million

Table 5c: Financing of planned activities to 2030

Parties	Implementation Instruments	Indicative financing contribution
Developing 15 storage projects in Europe		
The most promising storage projects in early evaluations will be progressed and additional projects identified and developed.		Total cost to be determined
		Total budget required: to be determined

R&I Activity 6: Developing next-generation CO_2 capture technologies

Responds to ***Target 6****: At least 3 pilots on promising new capture technologies, and at least one to test the potential of sustainable Bio-CCS at TRL 6-7 study*

Overview of existing and planned activities

Building industrial scale CCS projects will generate many new challenges that can best be solved by undertaking R&D in parallel with large-scale activities. An iterative process is needed where R&D projects address specific industrial challenges, with the results then implemented in large-scale projects. This may require networks where knowledge and experiences, as well as data gained, can be shared in a systematic way, and could include the following areas:

- Integration of CO_2 capture systems in power or industrial plants
- Heat integration and other environmental control systems (SOx, NOx, H_2S)
- Part-load operations and daily cycling flexibility
- The impacts of CO_2 composition and impurities, and concentration levels, amoung others, on CCU applications (see details under R&I Activity 7)
- Demonstration of novel capture technologies (advanced chemical looping and calcium looping systems, membranes, novel solvents and solid sorbents) at TRL6-7 for a range of industrial environments.

The data collected at the plants will be instrumental in validating and improving simulation tools, thus increasing the understanding of the process and help bringing costs down. A significant barrier to achieving open exchange of information, knowledge and experience is Intellectual Property Rights. The sharing may have to be limited to non-proprietary and generic data and environmental issues that the research and engineering communities can work on to bring costs down.

Within CO_2 capture, pilots are needed to ensure fast and cost effective R&D activities. New and emerging capture technologies are at very different stages of maturity, ranging from concepts to larger projects, i.e. at 20-30MW, or a capture capacity of up to a few hundred thousand tonnes of CO_2/yr. One challenge is to scale technologies from the concept stage to larger sizes as it requires large test facilities. Presently there are few large-scale test facilities and the existing ones are mainly for solvent-based post-combustion technologies. Development of novel capture technologies will benefit from international cooperation and burden sharing to establish a few large test facilities for other capture technologies in a network, building on the experiences from ECCSEL and from the existing base of pilots built under recent and ongoing EU research projects and from the International CO_2 Test Centre Network (ITCN).

The large-scale test facilities exist from some process routes, such as the Technology Centre Mongstad (TCM) in Norway, one of the most advanced and the largest post-combustion CO_2 capture pilots, where several vendors having already qualified their CO_2 capture technologies. Onwards to 2020, TCM could play a key role by providing test campaigns for new and innovative post-combustion technologies that can realise the efficiency and cost-effectiveness of CO_2 capture technologies in full-scale plants.

Recently the development of advanced, high-efficient supercritical CO_2 (S-CO_2) cycles using oxy-fired gas turbines is gaining an increasing interest worldwide as an advanced CO_2 capture technology able to meet the load flexibility requirements needed in the energy transition scenario. Existing proven power generation equipment can be adopted for S-CO_2 power cycle; however, research and development are needed for specific devices (i.e. high pressure oxy-combustor, water separation unit, heat exchangers) and or processes (i.e. purification of hot combustion gases, development of quick start-up strategies).

Identified gaps

There is need for similar size facilities for other capture technologies as well as those tailored to test and commercialise capture technologies required for specific industries, for example cement and steel.

Pathway to 2030 and beyond

Further innovation will require the creation of a demand for such novel CCS technologies by proving CCS as a decarbonisation via commercial scale demonstration projects and by developing incentives which provide a perspective for CCS; including these novel technologies to become commercial. In turn, this can then stimulate further innovation and learning through the creation of a competitive sector.

Collaboration should be initiated (and in some cases continued) between SET-Plan countries, the European Commission, and industry in 'Innovative Consortia', as well as the CCS and CCU clusters listed under R&I Activity 2, to drive forward the most promising technologies towards commercialisation.

As mentioned in the previous section, ACT is a European initiative to establish CO2 capture and storage as a tool to combat global warming. ACT has recently completed an open call for CCS projects, and eight new projects are planned to start in August 2017. The projects are expected to deliver results that can pave way for pilot testing of innovative CO2 capture technologies. ACT is planning new calls in 2018 and 2020 and projects emanating from the ACT calls can have relevance for further development of projects beyond 2020.

Development of novel CO_2 capture technologies to 2030 and beyond will require access to world class R&D infrastructure. The ESFRI project and European Research Infrastructure Consortium ECCSEL ERIC offers state-of-the art R&D laboratories related to development of CO_2 capture technologies. The synergies between ECCSEL ERIC and ambitious R&D actions within CO_2 capture will be essential for development of cost effective solutions. More details about ECCSEL ERIC is given under R&I activity 5.

Table 6a: DOI Targets and Monitoring Mechanisms

DOI Target	Monitoring mechanism
Target 6: At least 3 pilots on promising new capture technologies, and at least one to test the potential of sustainable Bio-CCS at TRL 6-7 study	• Funding secured under the Horizon 2020 2018/19 Energy Work Programme • Agreement on and implementation of large pilot test facilities for other capture systems than post-combustion • Project proposals for testing the potential of sustainable Bio-CCS at TRL 6-7 which are in line with the sustainable development policies of the EU • Pilots of emerging technologies tested at TRL5-7 and fitted to work with flue gas or boundary conditions, as present in large non-power industries. • Identification of a platform to share R&D knowledge and experience

Pathway to 2030 and beyond	Monitoring mechanism
Project proposals for scale-up of promising capture technologies that are applicable for power plants and energy intensive industries, in particular the iron, steel, cement and refinery sectors	• Recognition of technologies with the potential for greatest impact. • Understanding of the pathway to commercialisation. • Testing centres established for various capture routes. • Industry expresses an interest in public-private partnerships in order to invest and advance these technologies

Expected deliverables and timeline

Developing next-generation capture technologies

- Execution of larger pilots TRL 6-7 on technologies such as improved solvent and sorbent based systems, various membrane technologies and advances oxyfuel technologies (see Annex).
- Capture systems with 30 % reduced CAPEX and non-fuel OPEX compared to current state of the art, brought to TRL 6-7 with minimized environmental impact, capture rate at 90 % or more and flexibility with respect to large variability of load changes. A number small-scale capture projects have been identified which may support these outcomes (see Annex).
- Development of supercritical CO_2 power cycles with oxy-combustion gas turbines, TRL 5-6 [proposed]

Table 6b: Financing of planned activities to 2020

Project/Parties	Implementation Instruments	Indicative financing contribution
Continuation of activities at TCM		
Norwegian Government	Norway Grants 2014-2021	
Air Liquide, Gassnova SF, A/S Norske Shell, Sasol and Statoil ASA, AVR, National Research Councils, and other National funding agencies.	State funding Industrial funding	
Developing next-generation capture technologies		
Industry, both vendors and users; engineering companies; existing and new test facilities and infrastructure networks; research organisations; academia; funding agencies; and governmental CCS bodies.	Industrial funding State funding	A range of current pilots at TRL6-8 in Europe adapted/retrofitted to a range of new industrial settings and/or boundary conditions (see projects listed in annex) *STATUS: Ongoing*
As above	Industrial funding State funding	A range of new pilots built at TRL>6 to demonstrate new capture technologies in suitable industrial environments

		STATUS: Ongoing
		Total budget required: Total cost to be determined

Table 6c: Financing of planned activities to 2030 and beyond

Project/Parties	Implementation Instruments	Indicative financing contribution
Scaling-up of next-generation capture technologies		
Technologies with greatest potential identified and developed	State funding Industrial funding European Commission funding and support through future R&D strategies under Framework Programme 9	Costs to be determined
		Total budget required: Total cost to be determined

R&I Activity 7: CCU Action

Responds to ***Target 8:*** *At least 3 new pilots on promising new technologies for the production of fuels, value added chemicals and/or other products from captured CO_2,* and ***Target 9:*** *Setup of 1 Important Project of Common European Interest (IPCEI) for demonstration of different aspects of industrial CCU, possibly in the form of Industrial Symbiosis*[12]

Background and challenges

CO_2 from gaseous industrial effluents is an alternative carbon source for the production of materials, fuels, and chemicals. Previous sustainability assessments have demonstrated that certain CCU technologies may offer a lower carbon footprint than existing production routes, offering a net reduction of CO_2 emissions and other potential environmental benefits. Additionally, certain CCU technologies can contribute to renewable electricity storage and provide low carbon fuels for transport (addressing SET Plan - Action 8).

Many CCU projects have been initiated in Europe with the support of European and Member State funding schemes[13], with a number of these already reaching pilot, demonstration, or event commercial level (see projects listed in the project annex) Further strategic R&I actions are needed to ensure the scaling-up and commercialisation of production activities, improved and new technologies enabling more cost-competitive valorisation of CO_2, and longer term disruptive CCU technologies. There is also a need for detailed Life Cycle Assessments (LCA) of the sustainability impact of CCU-derived products, including of the net CO_2 reduction potential compared to benchmarks. Examples of the priority thematic areas are provided below:

Enabling competitive CO_2 valorisation

Reducing the capital intensity and energy footprint of technologies for the chemical valorisation of CO_2 are key elements to make these CCU technologies cost competitive. There are significant costs involved in the capture and purification of CO_2. Some CCU options can be developed to use gas streams with lower purification levels than those required for CCS. Research & development is necessary to define the minimum concentration/maximum impurities of CO_2 streams that the different conversion processes can tolerate, and develop optimised CO_2 capture and purification processes. Research and development is needed for more energy efficient capture and purification technologies and for improved robust catalyst systems, which could cope with less pure CO_2 sources, thus improving the overall energy efficiency of CO_2 valorisation processes. Modular and containerised approaches will also be developed for cost competitive solutions. In addition, a profiling of different stationary industrial CO_2 sources will determine preferential matching with the different potential CO_2 utilisation paths.

Carbonation of industrial wastes with CO_2

The carbonation of industrial waste and by-products is proven at commercial scale in specific configurations. This can represent permanent sequestration of CO_2 and reduce waste going to landfill and natural resource requirements. Carbonation processes can be applied to a range of industrial

[12] Important Projects of Common European Interest (IPCEI) are transnational projects of strategic significance for the EU. In 2014 the European Commission adopted specific State aid guidelines for IPCEIs (http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.C_.2014.188.01.0004.01.ENG) allowing Member States to provide financial support to such projects undertaken by industry beyond what is usually possible for R&D and innovation projects. For example, public funding may also support the first industrial deployment of the results of an R&D project and may cover a higher percentage of the funding gap. An example is the IPCEI on High Performance Computing (HPC) and Big Data Enabled Applications launched in January 2016 by Luxembourg, France, Italy and Spain (https://ec.europa.eu/commission/commissioners/2014-2019/oettinger/blog/luxembourg-launches-supercomputing-project_en).

[13] Including FP7 and H2020 at European Level, and national programmes such as: "Technologies for Sustainability and Climate Protection – Chemical Processes and Use of CO_2" and "CO2Net" from BMBF in Germany ; research programs from the British Engineering and Physical Chemistry Research Council; or research programs from ADEME in France.

mineral wastes and by-products, which are rich in calcium and magnesium silicates and oxides (e.g. fly ash and bottom ash from waste incinerators, cement bypass dust, steel slags) as well as historical deposits of such materials. A diverse range of products can be generated (e.g. aggregates, blends, binding agents, filler loads) for different application markets (e.g. building, roads, plastics, paper, etc.). Waste streams which offer the greatest opportunity to implement carbonation on a large scale in Europe need to be identified, with the aim of developing those with the greatest market value potential and customer acceptance, while not distorting existing markets.

Transformation of CO_2 and renewable energy into methanol (power-to-methanol via electrolysis)

Gaseous emissions containing CO_2 (and optionally also CO) from various industrial sectors can be converted to methanol through reduction with hydrogen, and used as a chemical building block or as a fuel. Pilot projects are needed to demonstrate that industrial gaseous flows can be integrated to produce methanol in a cost and energy-efficient manner. The major challenges lie in the integration and up-scaling of technologies that are at different TRL levels (from TRL 6 to commercial), the use of intermittent renewable electricity (with validation of the positive impact of stabilizing the power grid) and the development of regulatory incentives that create appropriate market conditions.

Transformation of CO_2 and renewable energy into chemicals and fuels (power-to-chemicals and fuels via syngas)

The integrated process of transforming power, CO_2, and water to syngas can enable the production of a variety of fuels or other hydrocarbons. This process has been proven on a test plant scale (TRL 6). A fully integrated demonstration scale unit (TRL 7-8) is now required, before progressing to commercial production (TRL 9). Besides total integration, the major challenge for the conversion process are to adapt to the intermittent nature of renewable electricity supply, to produce the right mix of different hydrocarbon products in function of market conditions, and to reduce operational costs. Also required is the development of a digitalised mechanism (e.g. based on the blockchain technology) for monitoring the balance of the centralised production of CO_2-derived fuels with the decentralised consumption within the European transportation network. This can establish a virtual accountability link between production and individual consumers, while the physical product stream is distributed through the existing fuel infrastructure.

Production of polymers from CO_2

The chemical valorisation of CO_2 into polymers has the potential to significantly reduce the carbon footprint of a range of polymer materials. A number of CO_2-to-polymer technologies and variety of new CO_2 based polymers, for various applications, could be demonstrated at pilot and small size production scale in the next 5 years.

Advanced solar chemicals and fuels from CO_2: direct utilisation or solar energy for CO_2 valorisation

Breakthrough technologies are required for the direct utilisation of sunlight (instead of renewable electricity) as an energy source to produce more efficiently large volume building blocks and energy carriers using CO_2 from industrial flue gases as carbon feedstock. Highly efficient and stable materials, as well as, advanced integrated photoelectrocatalytic systems have to be developed for such future efficient CO_2 valorisation technologies.

Identification of gaps

To bridge the gap between lab-scale pilots and pre-commercial pilots (i.e. larger-scale demonstrations) further development will be required to provide:

- More competitive access to CO_2 through more efficient capture and purification technologies;
- More efficient CO_2 valorisation process technologies;
- Reliable and widely accepted LCA methodologies to assess the sustainability of CO_2 valorisation products, compared to benchmarks, as needed to support decision-making.

The potential sustainability benefits (including net reduction of CO_2 emissions, reduction of the use of natural and fossil resources, valorisation of waste) of each CO_2 valorisation technology needs to be assessed, based on such widely agreed LCA based methodologies. This will be key in the design and justification of appropriate policy measures.

Pathway to 2030

The readiness of the various CCU technologies outlined above varies over the complete range of TRL levels: some technologies are already at pilot, demonstration or even commercial stage (listed in the project annex), while breakthrough innovation technologies (such as advanced solar chemicals and fuels from CO_2) are only at lab scale. Each technology will need to progress independently to reach commercial scale production and dissemination, according to the timeframes outlined in the monitoring mechanisms listed in the table below. *It should be noted that most projects listed above are expected to start immediately (i.e. in 2018) and are expected to reach industrial pilot, demonstration, or even commercial stage around 2020 to 2025. The definition of further activities for the period until 2030 will depend on the results achieved by 2020-2025 and has therefore been described in less detail below.*

Table 7a: DOI Targets and Monitoring Mechanisms

DOI Target	**Monitoring mechanisms to 2020**

Target 8: At least 3 new pilots on promising new technologies for the production of fuels, value added chemicals and/or other products from captured CO_2	*Enabling competitive CO_2 valorisation*
	• Proof of concept and development of:
	  ○ Improved robust catalyst systems
	  ○ Energy and cost competitive CO_2 capture and purification technologies from industrial flue gases
	• Development of modular containerised pilots at industrial sites
	
	Carbonation of industrial wastes with CO_2
	• Locations selected and technical specifications defined for at least 4 pilot plants (10-50 kt/year) focusing on different waste streams and end markets for products.
	Transformation of CO_2 into methanol
	• At least 1 pilot plant (5-10 ktons/year) using intermittent renewable electricity commissioned
	Transformation of CO_2 into chemicals and fuels
	• At least one pilot operational
	Production of polymers from CO_2
	• At least 2 pilot plants operational
	Advanced solar chemicals and fuels from CO_2

	• At least 1 pilot (TRL 6) started
Target 9: Setup of 1 Important Project of Common European Interest (IPCEI) for demonstration of different aspects of industrial CCU, possibly in the form of Industrial Symbiosis	
Pathway to 2030	**Monitoring mechanisms to 2030**
Several large scale commercial plants in place in Europe for each of the main CO_2 valorisation routes, i.e. carbonation, transformation into methanol, fuels and chemicals, and production of polymers	*Enabling competitive CO_2 valorisation* • Potential commercial-scale projects have been identified • Catalyst systems for CO_2 valorisation developed, which are less prone to catalyst poisoning and deactivation, lower cost, and operate at lower temperature and pressure. • Improved process analytical technology (PAT) development for on-line monitoring of CO_2 quality • Modular and containerised pilot facilities at industrial site *Carbonation of industrial wastes with CO_2* • By 2021, four pilot plants are operational (10-50 kt/year), and by end 2022 ready for commercial scale development. • By 2030, several large scale commercial plants valorizing each of the different waste streams demonstrated via the 4 pilot plants. *Transformation of CO_2 into methanol* • By 2025 at least 1 operational industrial plant producing 50-100 kt/year of methanol using one of the different CO_2/H_2 feedstock configurations. • By 2030, several large scale commercial plants. *Transformation of CO_2 into chemicals and fuels* • Production upscaled in 2022 to 10 million litres of hydrocarbons per year, with commercial scale production from 2023 • By 2030, several large scale commercial plants. *Production of polymers from CO_2* • By 2030 at least one large-scale commercial plants. *Advanced solar chemicals and fuels from CO_2* • Upscaling depending on results of the pilot

Expected deliverables and timeline to 2020

An agreed approach to determine sustainability and net CO_2 emission reduction potential will be applied to each deliverable:

Enabling competitive CO_2 valorisation

- Development and testing of catalyst systems for CO_2 valorisation, less prone to poisoning and disactivation, operating at lower temperature and pressure, produced at lower cost , **2020**
- CO_2 separation and purification membranes developed for direct use of flue gases in CO_2 conversion processes to chemicals, **2020**
- Development of improved process analytical technologies (PAT) for online monitoring of CO_2 quality, **2020**

Carbonation of industrial wastes with CO_2

- Inventory of potential waste streams, potential market size, and sustainability assessment including CO_2 emission reduction potential vs. benchmark of the products completed, and locations for 4 pilot plants (10-50 kt/year) and priority waste streams identified **2019-2020**.

Transformation of CO_2 into methanol

- At least 1 pilot scale project at TRL7 (5-10 kt/year) producing methanol from flue gas using intermittent renewable electricity, **2020**

Transformation of CO_2 into chemicals and fuels

- Demonstration of an innovative syngas production with > 70% total energy efficiency (power to syngas) and industrialisation from TRL 6 to 9, **2020**
- Demonstration of digital blockchain mechanism which can establish a virtual accountability link between centralized e-Fuel production and individual e-Fuel consumers, **2020**
- Pilot-scale production of syngas (> 1 MW/hour of syngas), and first conversion to hydrocarbon products (500k litres/year), **2020**

Production of polymers from CO_2

- At least 2 new pilot projects for the production of new or existing polymers based on CO_2 produced, with the carbon footprint of the products reduced by at least 15% compared to conventional fossil based products, **2020**.
  Advanced solar chemicals and fuels from CO_2
- At least 1 pilot (TRL6) started, **2020**.

Table 7b: Financing of planned activities to 2020

Project/Parties	**Implementation Instruments**	**Indicative financing contribution**
Enabling competitive CO_2 valorisation		
Industry, Member States, European Commission, with overall coordination at an EU level	Industrial funding State funding EU funding	See Table 7c
Carbonation of industrial wastes and by-products with CO_2		
Industry, Member States, European Commission, with overall coordination at an EU level	Industrial funding State funding EU funding	See Table 7c
Transformation of CO_2 into methanol		
Industry, Member States, European Commission, with overall coordination at an EU level	Industrial funding State funding EU funding	See Table 7c

Transformation of CO_2 into valuable chemicals and fuels		
Industry, Member States, European Commission, with overall coordination at an EU level	Industrial funding State funding EU funding	See Table 7c
Production of polymers from CO_2		
Industry, Member States, European Commission, with overall coordination at an EU level	Industrial funding State funding EU funding	See Table 7c
		Total budget required: See Table 7c for projected costs to 2030

Table 7c: Financing of planned activities to 2030

Project/Parties	**Implementation Instruments**	**Indicative financing contribution**
Enabling competitive CO_2 valorisation		
Industry, Member States, European Commission, with overall coordination at an EU level	Industrial funding State funding EU funding	Total indicative budget of €35 million to 2025 STATUS: proposed
Carbonation of industrial wastes with CO_2		
Industry, Member States, European Commission, with overall coordination at an EU level	Industrial funding State funding EU funding	Total cost for 4 pilot plants: approximately €10-20 million to 2022 - depending on the scale and level of flexibility to accept diverse waste streams. STATUS: proposed
Transformation of CO_2 into methanol		
Industry, Member States, European Commission, with overall coordination at an EU level	Industrial funding State funding EU funding	Total budget for 1 pilot scale plant (10 ktons/y): € 20 million to 2023 STATUS: proposed
Transformation of CO_2 into chemicals and fuels		
Industry, Member States, European Commission, with overall coordination at an EU level	Industrial funding State funding EU funding	Indicative budget €100 million for 1 pilot, over 4-year time period until commercial production, starting in 2023 STATUS: proposed
Production of polymers from CO_2		

Industry, Member States, European Commission, with overall coordination at an EU level	Industrial funding State funding EU funding	At least 2 pilot projects Indicative budget €70 million to 2022 STATUS: proposed
Advanced solar fuels and chemicals from CO_2		
Industry, Member States, European Commission, with overall coordination at an EU level	Industrial funding State funding EU funding	At least 1 photoelectrocatalytic process pilot with high efficiencies and scalability, including an assesment of sustainabiltiy and net CO_2 emission reduction potential vs. Benchmark Total estimated budget: €40 million to 2025 STATUS: proposed
		Total budget required: To be determined

R&I Activity 8: Understanding and communicating the role of CCS in meeting European and national energy and climate change goals

Responds to ***Target 10:*** *By 2020, Member States having delivered as part of the Energy Union Governance their integrated national energy and climate plans for after 2020, and having identified the needs to modernise their energy system including, if applicable, the need to apply CCS to fossil fuel power plants and/or energy and carbon intensive industries in order to make their energy systems compatible with the 2050 long-term emission targets*

Overview of existing and planned activities

Energy-systems modelling to understand the role of CCS

Successful deployment of CCS and CCU requires technology and policy to be developed in parallel. Action on technology improvement will reduce the costs related to CCS and CCU, but policies are required to support early deployment of CCS and CCU in Europe. Longer–term, CCS and CCU are expected to be deployed when the cost of emitting CO_2 becomes higher than the cost of CCS and CCU. Establishing appropriate policy mechanisms at a European and national level requires an understanding of the potential role of CCS and CCU in the coming decades through advanced energy systems and economic modelling.

One example for such a tool is the JRC-EU-TIMES model, operated by the Joint Research Centre, for assessing long term development pathways for SET-Plan technologies. The JRC-EU-TIMES model is able to capture the interaction between sectors, e.g. transportation and power. This enables the model to help in understanding cross-sector synergies (e.g. modelling the shared cost-benefits between CCS deployment in industrial, power, heat and transport sectors) or side effects, making the JRC-EU-TIMES model suitable to identify for example the opportunity cost for CCS, the incremental change in the system costs caused by CCS exclusion. Furthermore, the comprehensive integration of hydrogen as a low carbon energy vector and its production alongside CCS and CCU has been implemented in the JRC-EU-TIMES model. Methodological improvements of systemic modelling (in particular the interaction of the energy system with related fields) and concrete results for the role of CCS and CCU can be expected to materialise from recently started H2020 projects on modelling transitions pathways such as REEEM[14], SET-NAV[15], REFLEX[16] and MEDEAS[17].

Pan-European analysis should be complemented by regional and national energy system modelling that considers the role of CCS and CCU in the period to 2030 and beyond. In line with the JRC-EU-TIMES model regional and national assessments should focus on all sectors of the economy, consider cross sector synergies and explore the impacts of not deploying CCS and CCU at the national and regional level. This analysis will provide a key input to the development of the integrated national energy and climate plans under the new Energy Union Governance. In the UK analysis is undertaken on the actions and policies that are required to deliver on future carbon budgets under the Climate Change Act. This analysis is underpinned by detailed energy system modelling which highlights the role of different technologies across all energy sectors.

Understanding and communicating the socio-economic case for investing in CCS and CCU

Analysis from internationally respected organisations, including the IPCC and International Energy Agency, has identified CCS as a key technology to deliver on the Paris Agreement. Despite this evidence the value of CCS is often questioned and not yet integrated into national climate and energy

[14] http://www.reeem.org/
[15] http://www.set-nav.eu/
[16] http://reflex-project.eu/
[17] http://medeas.eu

policies. Further research is required into how the socio-economic benefits and the case for investing in CCS and CCU – where this contributes to net reduction in CO_2 - can be conveyed to Governments, key stakeholders and the public.

For example, Sweden is assessing the socio-economic prospects for deploying BECCS at the scales suggested in modelling scenarios through: 1) mapping prioritisations of BECCS among key actors and in national climate targets and strategies; 2) exploring factors that may influence preferences; and, 3) assessing how models can approximate BECCS' socio-economic dimension. The project provides crucial input to realistic mitigation scenarios and the incentives or disincentives for deployment of BECCS. In the UK, Government and a cluster of energy intensive industries located in Teesside have undertaken a study looking at the creation of a clean industrial development based around a CCS and CCU equipped industrial zone. The goal of the project is retain the regional industrial base, attract new investment and jobs and contribute to meeting the UK's climate change targets.

Policy actions to realise socio-economic benefits of CCS and CCU

Where the analysis above demonstrates the importance of CCS and CCU at the national level then it will be necessary for stakeholders – including European Institutions, national and regional governments and industry – to collaborate in the development and implementation of strategies, roadmaps and action plans that enable the further development and deployment of CCS and CCU in Europe. Taken as a whole the above actions will provide evidence base to support and justify the required investment in CCS and CCU.

Identified gaps

There is a need for significantly more analysis and understanding of long-term decarbonisation scenarios at the European, regional and national level as relatively few national governments have undertaken the detailed modelling work required. The Energy Union Governance arrangements could make a contribution to closing this gap. Activities to understand the socio-economic case for CCS and CCU deployment and the policy actions required to realise CCS and CCU are more fragmented and more significantly more initiatives are needed.

Pathway to 2030

R&I activity 8 should be considered an ongoing activity that is periodically reviewed and updated in light of increased understanding of the efforts needed to address CO_2 emissions and the role of CCS and CCU in industrial, energy and climate policy.

Table 8a: DOI Targets and Monitoring Mechanisms

DOI Target	Monitoring mechanism
Target 10: By 2020, Member States having delivered as part of the Energy Union Governance their integrated national energy and climate plans for after 2020, and having identified the needs to modernise their energy system including, if applicable, the need to apply CCS to fossil fuel power plants and/or energy and carbon intensive industries in order to make their energy systems compatible with the 2050 long-term emission targets	*Energy-systems modelling to understand the role of CCS and Understanding and communicating the socio-economic case for investing in CCS and CCU* • European countries have completed modelling work to determine the role of CCS and CCU in meeting their national energy and climate change targets. • Continuation of support for ETIP ZEP under Horizon 2020 Energy work Programme *Policy actions to realise socio-economic benefits of CCS and CCU*

	• National and European policies which currently support/act as a barrier to CCS and CCU projects have been identified.
Pathway to 2030 and Beyond	**Monitoring mechanism**
Policies in place which support the delivery of CCS projects	*Energy-systems modelling to understand the role of CCS and Understanding and communicating the socio-economic case for investing in CCS and CCU* • Periodic review and update of National and European energy-systems modelling demonstrating the role of CCS and CCU. *Policy actions to realise socio-economic benefits of CCS and CCU* • Periodic analysis of National and European policies which support/act as a barrier to CCS and CCU projects.

Expected deliverables and timeline

- Ongoing cooperation with the Dutch government to develop a CCS and CCU Roadmap in collaboration with industry in the Netherlands (oil and gas, power sector, industry) [ongoing]
- Swedish study on the socio-economic prospects for BECCS (P42390-1) [ongoing]
- Further engagement with CCS sand CCU and academic/modelling communities
- Knowledge sharing networks established

Table 8b: Financing of planned activities to 2020

Project/Parties	Implementation Instruments	Indicative financing contribution
Energy-systems modelling to understand the role of CCS		
Member States, European Commission, JRC	Horizon 2020 National Research Councils State funding	Costs to be determined
Support from the Zero Emission Technology and Innovation Platform		
Understanding and communicating the socio-economic case for investing in CCS and CCU		
Support from the Zero Emission Technology and Innovation Platform		
EERA CCUS to Contribute towards R&D actions		
Policy actions to realise socio-economic benefits of CCS and CCU		
National Governments and European Commission	State support European Commission support	Costs to be determined
		Total budget required: Costs to be determined

Table 8c: Financing of planned activities to 2030

Project/Parties	**Implementation Instruments**	**Indicative financing contribution**
Energy-systems modelling to understand the role of CCS		
Member States, European Commission, JRC, Zero Emission Technology and Innovation Platform	National Research Councils State funding	Costs to be determined
Understanding and communicating the socio-economic case for investing in CCS and CCU		
Support from the Zero Emission Technology and Innovation Platform		
EERA JP CCS to contribute to R&D actions		
Policy actions to realise socio-economic benefits of CCS and CCU		
National Government and European Commission	State support European Commission support	Costs to be determined
		Total budget required: Costs to be determined

Annex

a. Spreadsheet containing projects under R&I Activities 5, 6, and 7
b. Joint EERA and ZEP input to Horizon 2020 – January 2017