European Industrial Initiative on CO_2 Capture and Storage (CCS)

IMPLEMENTATION PLAN 2013-2015

Key actions to enable the cost-competitive deployment of CCS by 2020-25

CCS: a key enabler in the shift to a green economy

The critical role of CO_2 Capture and Storage (CCS) in decarbonising Europe is now indisputable: in the power sector it must account for 19-32% of the EU's total emissions reductions by 2050[1] according to the EU Energy Roadmap 2050. This means that "For all fossil fuels, Carbon Capture and Storage will have to be applied from around 2030 onwards".[2] Crucially, it will also complement intermittent renewable energy sources with low-carbon, baseload *and* balancing generation.

Yet the potential for CCS goes far beyond power, with other industrial applications expected to deliver half of the global emissions reductions required by 2050 from CCS.[3] Indeed, in some industries, such as steel and cement, it is the only means of achieving deep emission cuts. Combined with sustainable biomass (Bio-CCS), CCS can even *remove* CO_2 from the atmosphere – already recognised as a significant and attractive abatement solution.

There is no doubt that CCS can deliver, as confirmed by international developments where final investment decisions (FIDs) have already been taken on large-scale demonstration projects in Australia, Canada and the US. The ZEP cost reports[4] also give confidence that following a successful demonstration, CCS will be cost-competitive[5] with the full range of low-carbon power options, including on-/offshore wind, solar power and nuclear.[4]

Yet a 10-year delay in deployment will increase the global costs of decarbonising the power sector alone by $1 trillion.[3] A report published by Carbon Tracker and the London School of Economics also highlights that because CCS allows fossil fuels to be burned while *still* reducing emissions, it reduces the risk of 'unburnable carbon' which threatens the value of fossil-fuel assets worldwide (see page 7).

With investments potentially worth billions of euros annually, it is difficult not to conclude that Europe cannot grow or advance *without* CCS – environmentally, economically or competitively.

CCS is on the critical path to deliver the EU Energy Roadmap 2050

However, both the demonstration and deployment of CCS are under threat due to the fall in the price of Emission Unit Allowances (EUAs), not only reducing the amount of funding available for the 'NER 300' (see page 4), but undermining the long-term business case for CCS, which relies on a strong EUA price. Public and political resistance has also manifested towards onshore CO_2 storage.

Finally, no CCS demonstration project was awarded funding in Phase I of the NER 300 mainly because relevant governments were not able to confirm the level of co-funding they would provide. However, robust, viable projects are still being progressed in several European countries.

If urgent policy action is taken, CCS can still be commercially viable by 2020-25 and widely deployed by 2030

Urgent action is therefore needed at EU and Member State level to counteract these developments – keeping pace with that of well-advanced projects. It means implementing economic measures beyond the EU ETS in order to support first movers, driving down costs through investment in R&D and building public confidence through the demonstration of CO_2 storage – on- *and* offshore. European and international collaboration should also be intensified in order to increase knowledge sharing and accelerate deployment.

Above all, the unique societal benefits of CCS need to be communicated: it can not only deliver substantial emission reductions across a range of industries, but provide the catalyst for economic growth – creating *and* preserving jobs – while ensuring a diverse and reliable energy supply.

If such action is taken, it is clear that CCS can still be commercially viable by 2020-25 and widely deployed by 2030 – for the *cost-effective* decarbonisation of Europe.

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[1] The EU is committed to reducing GHG emissions by 80-95% by 2050 (from 1990 levels)
[2] http://ec.europa.eu/energy/energy2020/roadmap/doc/com_2011_8852_en.pdf
[3] International Energy Agency (IEA), 2013: www.iea.org/publications/freepublications/publication/name,38764,en.html
[4] Zero Emissions Platform (ZEP): www.zeroemissionsplatform.eu/library/publication/165-zep-cost-report-summary.html
[5] €70-90/MWh for CCS with coal, €70-120/MWh with gas, operating in baseload (7,500 hours equivalent full load each year); fuel costs for hard coal and natural gas are 2.0-2.9 €/GJ and 4.5-11.0 €/GJ respectively

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The CCS EII: uniting industry, research, NGOs, Member States and the Commission

Recognising the critical role CCS will play in decarbonising Europe, the European Commission launched a European Industrial Initiative (EII) on CCS as part of its Strategic Energy Technology (SET) Plan.

Represented by industry, research organisations and NGOs – delegated from the Zero Emissions Platform (ZEP: www.zeroemissionsplatform.eu) and the European Energy Research Alliance (EERA: www.eera-set.eu) – Member States and the European Commission, the CCS EII is a unique model for collaboration. Its goal: to identify priority actions and joint activities that will enable the cost-competitive deployment of CO_2 capture, transport and storage technologies by 2020-25.

1 Review of the CCS EII Implementation Plan, 2010-2012

1.1 Defining priority actions and KPIs

The first CCS EII Implementation Plan outlined priority actions for the period 2010-2012, in line with the CCS Technology Roadmap:[6]

1. *Deliver the EU CCS demonstration programme*: achieve FID for 10-12 projects, based on ZEP's proposal for an EU CCS demonstration programme",[7] and develop an active European CCS Demonstration Project Network[8] ("Project Network") to maximise knowledge sharing
2. *Focus R&D on facilitating CCS deployment*: launch and coordinate joint R&D programmes for CO_2 capture, transport and storage in order to drive down costs and facilitate long-term planning and deployment – with a key focus on lighthouse projects (see below)
3. *Undertake activities to support CCS implementation*: facilitate the transposition of the CCS Directive[9] (via the Information Exchange Group[10]); increase public awareness and support; and maximise international collaboration.

Prepared jointly by the European Commission ("the Commission"), Member States and industry, the Plan was endorsed at the first meeting of the EII in May 2010, prior to its official launch during the SET-Plan Conference in June 2010.

The Plan also defined indicative key performance indicators (KPIs) in order to review progress at regular meetings attended by the Commission, ZEP, the CCS Joint Programme of EERA (from 2011 onwards) and Member States.[11]

Definition of a lighthouse project, or large pilot

There are various types of large-scale pilot, also known as a lighthouse projects: a large pilot focused on CO_2 capture captures 50 to 100 tonnes of CO_2 per day; a large pilot focused on CO_2 storage stores 10,000 to beyond 100,000 tonnes of CO_2 per year during the R&D phase and may later be expanded into industrial-scale sites. Each pilot costs between ~€30 and €80 million.

1.2 Progress in meeting priority actions

1. Deliver the EU CCS demonstration programme

The EU CCS demonstration programme will build on experience gained from successful projects such as Sleipner, Snøhvit and large pilots such as K12B and Ketzin. However, it will now be considerably smaller than anticipated due to a variety of factors:

- The financial crisis and fall in the price of EUAs (€2.5-5/tCO_2 in Q2 2013), impacting not only the amount of funding available for the NER 300[12] scheme but the long-term business case for CCS, which relies on a strong EUA price
- Public resistance to onshore storage in some regions
- A weakening of political support in some Member States as a result.

Finally, no CCS project was awarded funding in Phase I of the NER 300 mainly because relevant governments were not able to confirm the level of co-funding they would provide. Phase II has now been launched and hopefully will result in the delivery of CCS projects, albeit well below the number envisaged

[6] Adopted in 2009 as part of the SET-Plan Financing Communication: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do? uri=CELEX:52009SC1295:EN:HTML:NOT
[7] www.zeroemissionsplatform.eu/extranet-library/publication/2-eu-demonstration-programme-co2-capture-storage.html
[8] www.ccsnetwork.eu
[9] Directive on Geological Storage of CO_2: 2009/31/EC
[10] http://ec.europa.eu/clima/policies/lowcarbon/ccs/implementation/index_en.htm
[11] Between 9 and 13 Member State representatives per meeting
[12] In 2008, the EU agreed to set aside 300 million Emission Unit Allowances from the New Entrant Reserve (NER) under the EU Emissions Trading Scheme (ETS) Directive to demonstrate CCS and innovative renewable energy technologies

when the competition was established. Notwithstanding a clear EU vision for CCS as a critical low-carbon energy technology, it would not have been possible for the CCS EII, with its present mandate, to have overcome such barriers.

2. Focus R&D on facilitating CCS deployment

The CCS EII Team was successful in agreeing and defining high-priority themes for R&D, such as CO_2 storage pilots, post-combustion capture and CCS for industrial applications. ZEP played a key role in this respect, providing input from the expressions of interest made by its members for projects which helped formulate the last two Seventh Framework Programme (FP7) calls.[13]

FP7-ENERGY calls have taken into account several of the priorities recommended by the first CCS EII Implementation Plan, including storage site characterisation (2010); high-efficiency post-combustion, solvent-based capture processes (2011); chemical and carbonate looping processes (2011); sizeable pilot tests for CO_2 geological storage (2012); impact of the quality of CO_2 on transport and storage (2012); and mitigation and remediation of leakage from geological storage (2013). However, the last two calls (FP7-ENERGY-2013-1 and 2) did not award any funding for CO_2 storage.

The composition of the CCS EII Team also benefited from the inclusion of the EERA, as requested by the SET-Plan Steering Group. Finally, the Commission, via SETIS,[14] set up a platform to collect and share information on nationally funded R&D projects aimed at stimulating cooperation within the CCS EII.

However, when discussing topics/types of projects that could contribute to meeting the objectives of the EII Technology Roadmap the limited resources were not taken sufficiently into account; nor was action taken to adjust the Implementation Plan accordingly. Despite a clear expression of interest by industry in lighthouse projects – including 50% co-financing – funding therefore did not materialise and it was necessary to resort to currently available funding instruments (i.e. FP7), leading to a major funding gap. On the other hand, one of the FP7 calls (FP7-ENERGY-2012-2) discussed did not receive any proposals, resulting in the reallocation of funds (€22 million) to other energy research topics.

There is therefore an urgent need to identify dedicated funding mechanisms suitable for lighthouse projects – combining funding from industry, the Commission and, if possible, national programmes; without such a mechanism, no Member State was in a position to make a firm commitment. Although a step-by-step approach was adopted (triggered by the SETIS project mapping activity), it was not particularly successful, as seen from the limited number of projects introduced by Member States to the SETIS database.

3. Undertake activities to support CCS implementation

The CCS Directive has been successfully implemented in a majority of Member States and the CCS Project Network is now established and active. However, storage site operators still need greater clarity in order to de-risk CCS investments – for example, on the precise modalities for site hand-over and financial security at Member State level. There is also an urgent need for Contracting Parties to ratify the amendment to Article 6 of the London Protocol in order to allow cross-border CO_2 transport and subsea storage. Finally, the CCS EII did not have a tangible impact on improving public awareness and support.

1.3 Key lessons learned

The composition of the CCS EII is key to its effectiveness and **high-level representation from Member States is essential** to achieving high-level impact on key issues, such as the delivery of political and legal support, and joint programming of R&D activities.

Lighthouse projects are critical to driving down the costs of CCS and accelerating deployment, yet still lack a suitable funding mechanism.[15] It is therefore essential to improve the exchange of information on R&D strategy and budgeting within the CCS EII Team and **urgently establish a dedicated and collaborative funding mechanism for such projects**.

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[13] FP7-ENERGY-2012-1, FP7-ENERGY-2012-2, FP7-ENERGY-2013-1, FP7-ENERGY-2013-2
[14] Strategic Energy Technologies Information System
[15] Experience in recent years shows that the main hurdles to CO_2 storage pilots relate to capital-intensive elements such as the drilling of wells and injection facilities, and the purchase of CO_2. However, it should be possible to achieve significant cost savings by using low-cost drilling technologies from the co-utilisation of mobile injection facilities between several pilot projects and using CO_2 from (for example) operating capture pilots.

Although significant progress was made in devising the first generation of KPIs, **KPIs must be revisited to ensure data collection is sufficient, meaningful and feasible** (see Annex III) and **short-term actions identified for the duration of the Plan itself** (see Annex IV).

1.4 The way forward

In line with the Commission's CCS Technology Roadmap, the CCS EII Implementation Plan for 2013-15 therefore has the following key priorities (Figure 1 below):

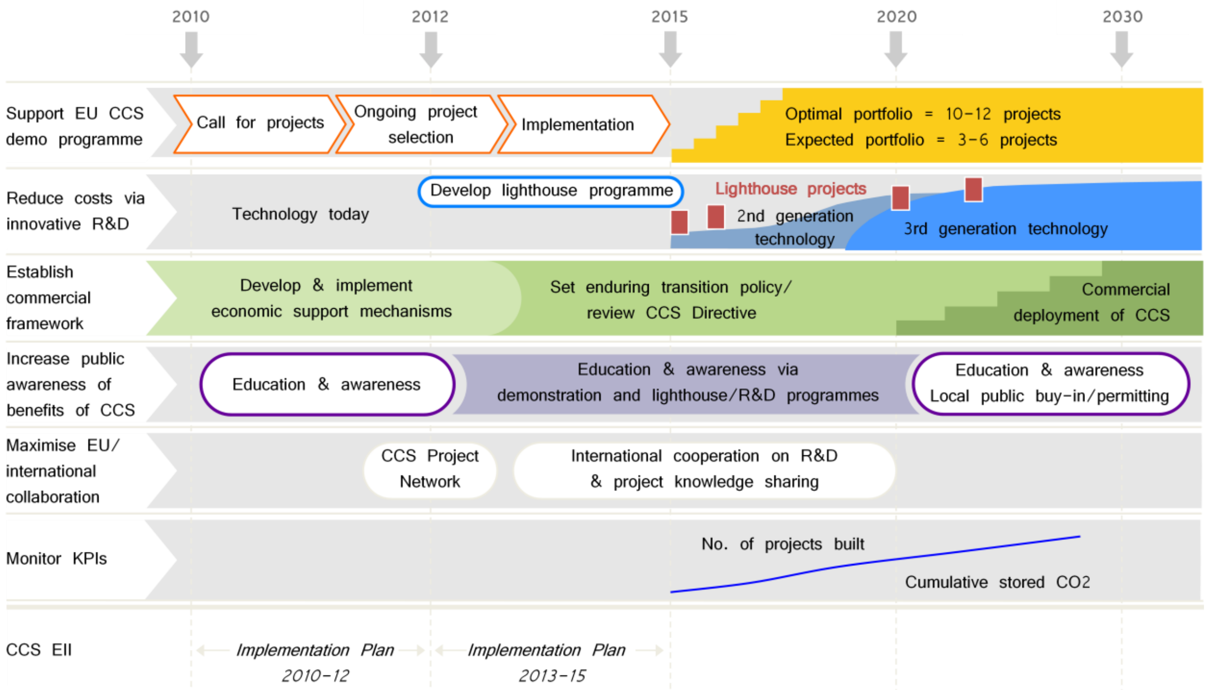

Figure 1: A forward view on CCS implementation

2 The CCS EII Implementation Plan, 2013-2015

2.1 Supporting the EU CCS demonstration programme

A typical energy technology pathway consists of three phases: (1) discover and develop (2) demonstrate and (3) deploy. With individual components of the CCS value chain – CO_2 capture, transport and storage – already proven, CCS is entering the demonstration phase for first-generation technologies during which complete value chains are scaled up so that:

- Industry can, inter alia, validate and prove the costs of CCS technologies – establishing the basis for future cost reductions from second- and third-generation technologies.
- Investors (financial, industrial, government) can invest confidently in full-scale projects. Early movers also pave the way for subsequent projects which can add to existing infrastructure, reducing commercial and technical risks considerably. Government gains information on the reliability, costs and unique benefits of CCS, supporting future energy policy decisions.
- The public gains a deeper understanding of the benefits of CCS and the safety of CO_2 storage.

An optimal EU CCS demonstration programme would cover the main capture technologies; CO_2 storage in deep saline aquifers and depleted oil and gas fields, on- and offshore; projects in both the power sector and other carbon-intensive industries; and for all the principal types of fossil fuels – a total of 10-12 demonstration projects. However, there will now be considerably fewer demonstration projects than anticipated due to the financial crisis and fall in the price of EUAs; public resistance in some regions; and a weakening of political support as a result.

'Unburnable' carbon that threatens fossil-fuel asset values

According to a report* published by Carbon Tracker and the London School of Economics, 60-80% of coal, oil and gas reserves cannot be burned if the rise in average global temperature is to stay below 2°C. This raises the prospect of vast wasted capital and stranded assets, with trillions of dollars of value wiped off the world's stock exchanges if countries live up to their agreements to act on climate change.** CCS would help avoid this by allowing fossil fuels to be burned while *still* reducing CO_2 emissions.

* http://carbontracker.live.kiln.it/Unburnable-Carbon-2-Web-Version.pdf
** http://gofossilfree.org/files/2013/02/HSBCOilJan13.pdf

Concerns have therefore been raised that CCS cannot progress from demonstration to wide deployment post 2030 in line with the EU Energy Roadmap 2050. However, historic precedents such as the introduction of flue gas desulphurisation in Europe and the US – a technology also driven by environmental concerns and underpinned by strong policy support – demonstrate that this is well within the capability of industry to deliver. This is confirmed by international developments where FIDs have already been taken on large-scale demonstration projects in Australia, Canada and the US.

The ZEP cost reports[16] also give confidence that following a successful demonstration, the current suite of CCS technologies will be cost-competitive[17] with the full range of low-carbon power options in Europe, including on-/offshore wind, solar power and nuclear. This is echoed in the report published by the UK's CCS Cost Reduction Task Force in May 2013.[18]

As no CCS projects have been awarded funding in Phase I of the NER 300, a successful Phase II is therefore essential to keep the EU CCS demonstration programme on track. A delay of even a few years will have a severe impact on the EU's climate goals – in the EU Energy Roadmap 2050, CCS plays a key role in *every* scenario. In this respect, the Commission's decision to bring forward the second call for

[16] www.zeroemissionsplatform.eu/library/publication/165-zep-cost-report-summary.html
[17] €70-90/MWh for CCS with coal, €70-120/MWh with gas, operating in baseload (7,500 hours equivalent full load each year); fuel costs for hard coal and natural gas are 2.0-2.9 €/GJ and 4.5-11.0 €/GJ respectively
[18] A collaboration between Department of Energy and Climate Change, The Crown Estate and industry: www.gov.uk/government/publications/ccs-cost-reduction-task-force-final-report

proposals is a very helpful intervention and means projects can still be operational by 2020, enabling wide deployment by 2030.

2.1.1 Accelerate the application of CCS in industries beyond power

The application of CCS to industrial sectors beyond power (e.g. steel, cement, refining) is expected to deliver half of the global emissions reductions required by 2050 from CCS.[19] If different CO_2 sources are located in close proximity, they can also share CO_2 transport and storage infrastructure, thus benefitting from economies of scale. The cost of CO_2 capture for industrial applications varies but may, in many cases, be lower than for power generation due to a higher concentration of CO_2 in the exhaust gas. Yet many of these industries face a high risk of 'carbon leakage'[20] due to the global trade of their products. Additional measures are therefore needed to create a long-term business case for CCS. Indeed, in some industries (e.g. steel and cement), it is the only means of achieving deep emission cuts.

In July 2013, ZEP published a landmark report, "*CO_2 Capture and Storage (CCS) in energy-intensive industries: an indispensable route to an EU low-carbon economy"*.[21]

2.1.2 Exploit the full potential of Bio-CCS

The same may also be true for the combination of CCS with renewable energy and fuels production using biomass feedstocks.[22] With experts now[23] indicating that more powerful technologies are required to keep global warming below 2°C, there is an urgent need for carbon-negative solutions such as Bio-CCS[24] – the only large-scale technology that can *remove* CO_2 from the atmosphere.

A recent study[25] indicated that in Europe, Bio-CCS could theoretically remove 800 million tonnes of CO_2 from the atmosphere every year by 2050 using all available sustainable biomass for firing in power plants – equivalent to over 50% of current emissions from the EU power sector. This is in addition to any emissions reductions achieved by replacing fossil fuels with that biomass. As indicated, the sustainability of biofuels must be taken into careful consideration when addressing the Bio-CCS agenda.

Use of biofuels and bioenergy is steadily increasing in the EU due to targets for renewable energy sources and certain biofuels production routes could provide 'low-hanging fruits' for early, low-cost CCS deployment; in the US, Bio-CCS is already being deployed at industrial scale.[26]

2.1.3 Key actions

- Monitor the progress of the EU CCS demonstration programme and recommend interventions if progress deviates substantially from plan.
- Review mechanisms urgently needed to enable demonstration projects to take FID: a successful demonstration of CCS is a precondition for commercial deployment; but without a secure environment for long-term investment, demonstration projects will not happen. CCS deployment in industrial applications should be given specific attention as securing a long-term business case is likely to require different measures to those in the power sector, not least due to concerns surrounding 'carbon leakage' in a global market (see section 2.3.1).
- Assess if support is needed for demonstration projects that have taken FID.

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[19] 2009 IEA CCS Technology Roadmap: www.iea.org/publications/freepublications/publication/CCS_Roadmap-1.pdf
[20] "Carbon leakage" refers to the relocation of investment in carbon-intensive activities to countries where there are fewer constraints on emissions
[21] www.zeroemissionsplatform.eu/library/publication/222-ccsotherind.html
[22] Including municipal and other wastes
[23] For example, "The Technology Roadmap Carbon Capture and Storage in Industrial Applications", jointly published by the IEA and the United Nations Industrial Development Organization (UNIDO), 2011: www.unido.org/fileadmin/user_media/News/2011/CCS_Industry_Roadmap_WEB.pdf
[24] "*Biomass with CO_2 Capture and Storage (Bio-CCS) – The way forward for Europe*", published by ZEP and the European Biofuels Technology Platform: www.zeroemissionsplatform.eu/library/publication/206-biomass-with-co2-capture-and-storage-bio-ccs- the-way-forward-for-europe.html
[25] IEA Greenhouse Gas (GHG) Programme. Comprehensive life-cycle analyses (LCAs) for the carbon balance of biomass supply and conversion routes should be performed to verify these numbers.
[26] The ADM bioethanol-CCS project

2.2 Reducing the costs of CCS through innovative R&D

As with all technologies, CCS will benefit from ongoing R&D in order to further drive down costs. In addition to large-scale demonstration projects, the optimisation of current and next-generation technologies is therefore also needed to enable rapid, efficient and cost-effective deployment post-2020.

The first CCS EII Implementation Plan listed potential large-scale R&D pilots (known as lighthouse projects – see page 4), as key to driving down the costs of CCS through developing second-generation capture technologies. Yet to date none has materialised due to the lack of a suitable funding mechanism. It is equally important that second and third-generation capture technologies are further developed.

Public and political resistance has also manifested towards onshore CO_2 storage. Given that the lack of proven, affordable, *local* CO_2 storage sites is a key barrier to the development of CCS in Europe, it is vital to develop large-scale storage pilots in order to build public confidence. In the context of pilots, it should be noted that the ECCSEL[27] project, backed by Member States via the ESFRI[28] labelling mechanism, aims to gather, streamline and further develop major European CCS R&D facilities (from laboratory facilities to large pilots) into a single, open, world-class infrastructure. ESFRI will also shortly be publishing an overview of the size, status and organisation of research efforts on CCS across Europe.

Finally, studies of complete energy systems should be undertaken where power plants with CO_2 capture (transport and storage) complement a high share of renewable energy sources. This relates both to high requirements for load-following capabilities, as well as capturing CO_2 from biomass/biomass fuels; plant availability and operability; and variations in design between base-load power and load followers.

2.2.1 CO_2 capture: optimise first-generation technologies and advance next-generation

In the power sector, first-generation CO_2 capture technologies have been tested at large pilot-scale facilities for all three capture pathways (post-combustion, pre-combustion and oxy-fuel) and each process is now in the demonstration phase.

However, existing large capture pilot-scale plants[29] should continue to be financed as ongoing R&D will lead to capture cost reductions by improving component performance and capture processes. They will also provide critical support to the first demonstration plants by offering facilities to help with the optimisation of processes and problem-solving; and provide valuable test beds for demonstrating the operational flexibility of capture plants and ensuring that they do not impose any operational restrictions on the plant. Finally, they may also facilitate the validation of the technologies for use in industries beyond power (see section 2.1.1).

Further R&D, including pilot-scale testing, is also needed to develop second- and third-generation technologies that will potentially reduce investment and operating costs, as well as the energy penalty. This includes the development of new or optimised solvents, sorbents and membranes, new process designs and novel power plant integration schemes. Cross-cutting issues, such as operational flexibility (a requirement for non-renewable power plants in the energy markets) should also be addressed. Finally, capture pilots could potentially supply CO_2 to large-scale storage pilots, for which it is very difficult to purchase up to 100,000 tonnes of affordable CO_2.

For *post-combustion capture*, the highest R&D priorities for the power sector are 1) large pilot-scale R&D to support demonstration projects (see above); assess plant flexibility and operability issues; understand solvent degradation and emissions; improve solvent management of (mixed) solvents and/or scale up solid sorbent systems; and validate innovative process modifications 2) laboratory-scale R&D for innovative solvents, including dedicated process development and integration and 3) breakthrough, third-generation systems. All these processes also need to be adapted to other industries.

For *pre-combustion capture*, further research is required on 1) process integration in IGCC or hydrogen production processes at large pilot-scale 2) the scaling-up of sorption-enhanced water gas shift and 3) new technologies based on membrane or sorption-enhanced reforming systems in laboratory pilots. All these studies are required for both power *and* industrial applications.

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[27] European Carbon Dioxide Capture and Storage Laboratory Infrastructure: www.eccsel.org
[28] European Strategy Forum on Research Infrastructures: http://ec.europa.eu/research/infrastructures/index_en.cfm?pg=esfri
[29] See Annex I, page 15

For *oxy-fuel capture,* the highest R&D priority for first-generation technologies (pulverised fuel and circulating fluidised bed boiler configurations) is the further optimisation of the cycle, system integration (including oxygen production and CO_2 purification) and materials research in oxy-fuel environments. Second-generation oxy-fuel systems require validation in large pilot plants, while third-generation technologies (such as chemical looping combustion of solid fuels and oxygen production with membranes and sorbents) need to be studied at larger laboratory scale.

An additional, high-priority cross-cutting issue is the need to determine the viability and costs of various Bio-CCS routes and the validation of these advanced concepts in pilot projects. The impacts of biomass co-processing (including waste fuels where possible) on the CCS system also require further investigation.

Finally, the European Benchmarking Taskforce, which compares the efficiency and cost calculations of capture technologies, has already been established within FP7. This work should continue using additional criteria (e.g. environmental) in order to obtain a fair comparison of new and emerging technologies when limited cost and energy consumption data are available. The dynamic modelling of power plants with CCS should also have a higher priority.

More details on CO_2 *capture R&D priorities can be found in Annex I.*

2.2.2 CO_2 transport: accelerate the development of CO_2 infrastructure

In FP7, CO_2 transport projects focused on the various aspects of transport infrastructures are needed to enable the large-scale deployment of CCS in the EU, as well as a techno-economic assessment of the impact of impurities in CO_2, fluid properties, phase behaviour and chemical reactions in pipelines. Research in the field of CO_2 transport should focus on pipeline materials, including the impacts of irregular and seasonally varying operations and possible leakage scenarios; and on strategies and concepts for setting up a transport infrastructure, including opportunities for creating CO_2 source clusters, combining on- and offshore transport, and transporting CO_2 in challenging environments, such as populated areas.

Further R&D is also needed on start-up and stop, two-phase flow and phase changes in the pipeline. Finally, R&D support is required to support the development of international standards for CO_2 transport. *More details on* CO_2 *transport R&D priorities can be found in Annex I.*

2.2.3 CO_2 storage: prioritise the development of large pilots

The availability of storage sites and associated technologies is of critical strategic importance to CCS deployment. In recent years, significant progress has been made in site characterisation methods and methodologies, monitoring tools and approaches, and the efficiency of storage operations.

However, a current lack of large storage pilots poses a major obstacle to advancement. While some laboratory-scale research remains to be performed, up to six new storage pilots are urgently needed to validate/further improve characterisation, exploitation and monitoring techniques in ‘real-life’ geological conditions. Complementing NER 300 and EEPR[30] projects, the pilots will also play a key role in building public confidence, finalising regulatory issues and, in certain cases, exploring industrial-scale storage in the same reservoir. Several sites are required in order to cover different geologies and storage options, on- and offshore.

Although the main focus should be on deep saline aquifers, these may also be combined with depleted oil/gas fields or Enhanced Oil/Gas Recovery (EOR/EGR). Smart, flexible solutions to equipment needs are important for CO_2 storage pilots where issues such as the safe and economical refurbishing of oil and gas installations for CO_2 require investigation. For all pilots, securing large volumes of CO_2 is key to success.

Large-scale storage pilots will therefore enable the following R&D priorities to be carried out in situ:

1. *Site characterisation*: better understanding and improved coupling of multi-phase flow, thermodynamics, geochemistry and geomechanics (including faults and fractures)
2. *Monitoring*: enhanced leakage detection and measurement, both in situ and by remote sensing, and biological monitoring for environmental impact assessment

[30] European Energy Programme for Recovery

3. *Safe and efficient storage exploitation*: application of low-cost, diamond core drill rigs for exploration and monitoring wells; methodologies for pressure management, enabling optimal use of the subsurface storage space; testing of injection strategies; improved prediction of geologically controlled CO_2 leakage mechanisms; and testing of novel remediation technologies.

More details on CO_2 storage R&D priorities can be found in Annex I.

2.2.4 Develop a comprehensive European storage atlas

Europe is falling behind other global players in developing a European-wide CO_2 storage atlas, yet it is vital to advancing the commercial deployment of CCS – in the timeframe needed. Without it, it will also not be possible to progress the development of CO_2 transport infrastructure. ENeRG has therefore published a position paper[31] highlighting the urgent need for an interactive, web-based CO_2 storage atlas with data on the locations and storage potential of various storage options.

Some Member States have already made good progress in mapping CO_2 storage sites, e.g. in June 2013, the UK launched CO2Stored,[32] a web-enabled database of over 600 sites. The Norwegian Petroleum Directorate (NPD) has also issued a storage atlas[33] for the Norwegian part of the North Sea. Finally, FP7 has supported projects such as COMET, which studied the techno-economic feasibility of integrating CO_2 transport and storage infrastructures in the Western Mediterranean (Portugal, Spain and Morocco).

2.2.5 Explore the potential of CCUS to advance deployment

Increasingly, CO_2 Capture, Use and Storage (CCUS) is being discussed as a means of accelerating the deployment of CCS and lowering costs. This is largely driven by extensive US experience in CO_2-EOR, but also encompasses a range of applications including chemicals manufacturing, food and drink production, and other processes. In order to qualify as a climate mitigation technology, it is crucial that CCUS applications can demonstrate the long-term storage of CO_2.

CO_2-EOR currently accounts for over 60% of CO_2 used for industrial processes, according to a report published by the GCCSI: “Accelerating the Uptake of CCS: Industrial Use of Captured Carbon Dioxide”.[34] However, there is a range of technical and non-technical prerequisites required for a CO_2-EOR project to benefit the CCS industry, and given the number of factors that need to align to create early CCUS projects, CO_2-EOR and CCS should currently be considered as separate industries. It is particularly important to address the gap between CO_2 costs that EOR projects can economically justify and the costs of CO_2 capture from power plants. If all these issues are addressed, there is an opportunity for “industrial symbiosis”, i.e. one industry’s waste is another’s feedstock, while benefiting from a shared infrastructure.

For example, if governments support the development of CCS, CO_2 will increasingly become available and at lower cost, potentially enabling CO_2-EOR, EGR (Enhanced Gas Recovery) and other CO_2-usage projects to proceed that previously could not. The development of a flexible CO_2 pipeline and storage network will also improve the ability of these projects to maximise value by better managing CO_2 supply fluctuations and varying requirements – while reducing the investment burden for pilot projects which are sometimes needed to confirm if full-scale projects can go ahead. There is a further requirement to co-optimise EOR and CO_2 storage.

Since CO_2-usage projects generate additional revenue for governments and additional gains in GDP via associated economic activity, the longer-term benefits of stimulating a CCS industry, and the symbiotic relationship between CCS and CO_2-usage, could be significant.

2.2.6 Key actions

- Discuss and agree activities for advancing large pilots for both CO_2 capture and storage (lighthouse projects), including cross-cutting activities.
- Discuss and agree activities for advancing long-term R&D for second- and third-generation technologies.

[31] European Network for Research in Geo-Energy: www.energnet.eu/position_paper-storage-atlas_2012.pdf
[32] www.co2stored.co.uk
[33] www.npd.no/en/Publications/Reports/CO2-Storage-Atlas-/
[34] Global CCS Institute, 2011: www.globalccsinstitute.com/publications/accelerating-uptake-ccs-industrial-use-captured-carbon-dioxide

- Identify funding needs and models for R&D, large pilots and demonstration projects.
- Support the development of natural gas CCS and demonstrate its load flexibility in future energy systems, also when combined with renewables.
- Promote and review proposals to utilise clustered on-/offshore storage options.
- Support the development of CCS in industrial applications and their integration into transport/storage infrastructure clusters.
- Support the integration of biomass/municipal wastes in the CCS chain and the integration of biogenic CO_2 sources into transport/storage infrastructure clusters.
- Explore the potential for CCUS projects to advance CCS deployment.

2.3 Establishing the commercial framework for CCS in Europe

CCS is at a different stage of technological and commercial maturity from other low-carbon energy technologies, with unique aspects that can only be addressed by specific policy measures:

- CCS requires very large, upfront investments – not only for CO_2 capture, but also CO_2 transport and storage infrastructure. Timelines for individual elements of the CCS value chain differ, with storage requiring much longer lead times (up to 7 years).
- CCS technology is proven, but needs to be scaled up to large integrated projects, with significant potential to drive down costs.
- CCS must play a significant role in the future energy mix if decarbonisation targets are to be met: unlike intermittent renewable energy sources, CCS can deliver both base-load power generation *and* balancing capacity.
- CCS marginal costs are also highly dependent on fuel costs (fossil fuel and/or biomass/municipal wastes).
- CCS is necessary to decarbonise large parts of European industry, and measures should be considered to avoid carbon leakage impact on industry which is willing to take the first steps toward such large-scale decarbonisation.

2.3.1 Review mechanisms needed to keep CCS on track to achieve EU climate goals

Industry has already demonstrated its willingness to take on a major portion of the costs and risks of investing in CCS technology. However, the fall in the price of EUAs threatens both the demonstration *and* deployment of CCS in Europe: not only is significantly less funding available for the 'NER 300' scheme, but the long-term business case – which relies on a strong EUA price – has been seriously undermined.

Urgent action is therefore needed at EU and Member State level in order to provide investors with a strong price signal for investment:

- Ensure CCS is fully integrated into a holistic Energy and Climate Policy framework for 2030. This should be coordinated with structural reform of the ETS in order to strengthen the EUA price as it not only underpins the long-term business case for CCS, but also partly the short-term, as even demonstration projects will need to recover their investment over the medium to long term.
- Review mechanisms urgently needed to keep CCS on track to achieve EU climate goals.
- Develop effective business models for CO_2 transport and storage infrastructure. Large-scale CCS requires a CO_2 transport infrastructure of considerable legal and commercial complexity. However, if different CO_2 sources are located in close proximity, they can share both transport and storage infrastructure, thus benefitting significantly from economies of scale. With lead times of 6 to 10 years, early strategic planning is therefore vital. For more details, please refer to ZEP's report, *"Building a CO_2 transport infrastructure for Europe".*[35]

[35] www.zeroemissionsplatform.eu/library/publication/221-co-2transportinfra.html

In response, ZEP has published a report: "*CCS: creating a secure environment for investment in Europe*", [36] which provides concrete recommendations for economic support measures needed in the short, medium and long term, and which are fully in line with the recent work of the IEA.[37]

In March 2013, the Commission also launched a Consultative Communication on "The future of Carbon Capture and Storage (CCS) in Europe",[38] with the aim of initiating a debate on the options available to ensure its timely development.

2.3.2 Provide a strong regulatory framework and manageable risk exposure

In order for CCS to become commercially viable, industry also needs a strong regulatory framework and a manageable risk exposure, with standards and specifications aligned EU-wide so that free flow of CO_2 to the best storage opportunities can take place.

2.3.3 Key actions

- Raise awareness with the SET-Plan Steering Group of the commercial framework needed and keep CCS on track to achieve EU climate goals:
  - Review mechanisms needed in the short, medium and long term; however, the earlier they are *all* adopted, the greater the impact on earlier stages due to anticipation effects. This includes industrial applications which require direct funding in order to be able to survive in a competitive environment.
  - Provide feedback on the review of the CCS Directive in 2015.
  - Develop effective business models for CO_2 transport and storage infrastructure.
  - Review policy measures underway to achieve EU climate goals.

- In order to fulfil the significant potential of Bio-CCS, raise awareness of the urgent need to:
  - Reward negative emissions via the capture and storage of biogenic CO_2 under the EU ETS, to the same extent as for fossil CCS: abating biogenic CO_2 emissions must be treated in the same way as abating any CO_2 emissions as they have the same impact on climate change.

2.4 Increasing public awareness of the societal benefits of CCS

CCS is a key enabler in the shift to a green economy, yet the largest survey of public awareness of CCS in the EU (Eurobarometer) shows that only 1 in 10 claims to know what it is. However, public endorsement will be crucial in determining the role CCS plays in the future energy mix.

Member States, EU institutions, industry, the R&D community and NGOs should therefore work together to clarify any storage-related issues, highlighting the use of natural mechanisms that have already 'stored' CO_2, oil and gas underground for millions of years. The technology for CO_2 storage is also virtually identical to that used by the oil and gas industry for decades – to store natural gas underground or for EOR.
A limited number of CO_2 storage demonstrations have been taking place successfully in Europe since 1996, but these are not widely known to the general public. New regional, large-scale storage pilots will therefore significantly increase public confidence as open-access laboratories, with independent research organisations playing a major role and local communities actively involved.

2.4.1 CCS: supporting the environment, economic growth, local jobs *and* energy security

The unique societal benefits of CCS should also be communicated in terms of:

- *Substantial emissions reductions* across a range of industries, including applications beyond power (e.g. steel, cement, iron, chemicals, aluminium, fertiliser, refineries, pulp and paper). Sustainable biomass with CCS is also the only large-scale technology that can *remove* CO_2 from the atmosphere and deliver carbon-negative solutions (power production, biofuels production and industrial applications) – see page 8

- *Economic growth*, including job preservation *and* creation: for some sectors (e.g. steel, cement), CCS is the *only* large-scale abatement option available

[36] www.zeroemissionsplatform.eu/library/publication/211-ccs-market-report.html
[37] "A Policy Strategy for Carbon Capture and Storage", 2012: www.iea.org/papers/2012/policy_strategy_for_ccs.pdf
[38] http://ec.europa.eu/energy/coal/ccs_en.htm

- *Security of energy supply*: CCS can complement intermittent renewable energy sources with both low-carbon baseload power generatio*n and* balancing capacity.

Here, both demonstration and pilot projects will play a vital role in building public awareness and confidence, EU-wide.

2.4.2 Key actions

- Identify and, where appropriate, facilitate the implementation of measures to increase public and political awareness and support for CCS.
- Assess the suitability of launching a call for academics and other institutions to submit papers on the societal and economic impacts of CCS.

2.5 Maximising the potential of CCS via European and international collaboration

Collaboration over what works and does not work is key to accelerating CCS cost reductions. Knowledge obtained in EU-funded and other demonstration projects should therefore be shared with the scientific and engineering community in order to improve first-, second- and third-generation technologies. Information shared with the wider public will also build confidence in the transport and storage of CO_2. While the intellectual property of different organisations should be protected, fora such as the CCS Project Network, GCCSI and ZEP are important examples of how this can be done effectively.

Over the next three years it will therefore be important to leverage the true potential of the CCS Project Network in order to support the successful execution of the demonstration projects; there is also knowledge that Europe can share and gain through bilateral and multinational collaboration. International knowledge sharing will become increasingly important if the EU CCS demonstration programme fails to deliver a sufficient number of projects.

2.5.1 Key actions

- Monitor the number of demonstration projects in the CCS Project Network and new international knowledge sharing initiatives and provide guidance, as appropriate; support knowledge sharing between demonstration projects and large R&D pilots; and in general, between regional initiatives, industry and the R&D community.
- Encourage industry, the Commission and Member States to continue to grow CCS networks internationally through bilateral initiatives and fora such as the Carbon Sequestration Leadership Forum, IEA, Clean Energy Ministerial and GCCSI – including engagement and joint activities with developing countries.
- Continue and intensify a regular information exchange on national CCS R&D activities aimed at synchronising all relevant Member State research programmes; also involve international organisations in order to include non-European CCS R&D activities.
- Ensure that CCS applications in industries beyond the power sector are included in any relevant knowledge sharing and exchange processes.

Annex I: R&D priorities

CO_2 capture

a) Post-combustion capture

In FP7, most CO_2 capture research was dedicated to the development of more efficient solvent systems and processes. Several solvents have been identified and tested in industrial pilot-scale plants – plus some process modifications – with much fundamental knowledge on solvents, solvent degradation, solvent emission, solid sorbents and polymeric membranes gathered.

There has also been substantial progress in the development and pilot-scale demonstration of post-combustion calcium looping technologies, confirming the potential of this technology option. Although a substantial reduction in energy penalty has been achieved, further reductions are needed – and expected: current solvent systems operate with an energy demand approximately twice the theoretical minimum.

COLOUR CODES

Green *requires progression from pilots to demonstration/early commercial plants*
Yellow requires applied research, including pilots
Red *requires basic research*

	-2020	2020-2030	2030+
Develop robust, non-toxic and environmentally friendly liquid solvents with energy requirement < 2.5 GJ/tonne of CO_2 for power and industrial sectors			
Develop robust, non-toxic and environmentally friendly liquid solvents with energy requirement < 1.5 GJ/tonne of CO_2 for power and industrial sectors			
Calcium looping (a.k.a. carbonate looping): scale up and validate Circulating Fluidised Bed carbonator and alternative calciner designs; address issues related to chemical and mechanical stability of sorbent			
Develop high-temperature solid sorbents other than natural $CaO/CaCO_3$			
Low-temperature solid sorbents: increase capacity, adsorption rates and selectivities under low partial pressures of CO_2			
Membranes: develop cheaper and more robust membrane modules with high permeability and selectivity			
Cryogenics: demonstrate anti-sublimation process			
Hydrates: increase selectivity and kinetics			
Gas turbine development for CO_2 (exhaust gas recycling) and/or O_2 enrichment: adapt and optimise configuration for CO_2- and/or O_2-enriched atmospheres (in particular combustion stabilities) and advance cost-effective schemes, including system optimisation			
Minimise overall energy penalty for flue gas cleaning and CO_2 compression system and in the steam cycle configuration			
Membrane-supported liquid solvents: increase selectivity and kinetics			

*Maturity will depend on the solvent under consideration. For MEA, the colour code is green from 2020.
**Maturity will depend on the solvent or sorbent under consideration

Expected impacts for delivery of the SET-Plan:

- Improved solvent management, based on mixed solvents, ready for piloting
- One or more new solvents and solid sorbents, with significantly lower regeneration energies, ready for piloting
- Calcium-oxide looping, optimised and demonstrated in pilot-scale plants for coal, gas and biomass process configurations, ready for scale-up to multi-MW demonstration
- Post-combustion capture technologies in all types of CO_2-intensive industries (e.g. cement, steel, refineries and petrochemicals, aluminium), ready for demonstration.

b) Pre-combustion capture

In FP7, most R&D activities on pre-combustion capture were dedicated to novel CO_2/hydrogen separation systems and integrated capture installations aimed at high efficiencies and low capture costs. Several are now ready for large-scale pilots, not only in power generation but also other industries (e.g. steel, refineries).

	-2020	2020-2030	2030+
Oxygen production for pre-combustion applications			
Advanced cryogenic distillation and integration with other parts of the plant in order to reduce energy consumption by up to 40 kWh/tonne			
Flexible cryogenic air separation with improved turndown and load-following capabilities with minimal impact on O_2 purity and specific power consumption			
Develop O_2-separating membranes (flux, stability, manufacturing)			
Develop O_2-separating adsorbents (O_2 capacity, stability, manufacturing)			
Gasification			
Improved plant systems: coal feeding, slag and fly ash removal			
Increase efficiency of converting the chemically bound energy of the coal into that of the flue gas (cold gas efficiency)			
Reduce the amount of the required gasification agent (especially oxygen requirements)			
Further develop the raw gas cooling system (efficient energy use)			
Understand material-related consequences in gasification processes (EA)			
Model reactive multi-phase flows for developing reaction compartments and reactor geometries (EA)			
Establish databases as a basis for material and process modelling (EA)			
Model the dynamic behaviour of gasifiers for optimising process control of individual plant components (EA)			
Water-gas-shift			
Further develop shift catalysts to improve activity and stability, and reduce steam demand			
Develop sour shift catalyst with higher activity, improved stability and low steam demand			
Improve WGS reactor design. Develop isothermal designs.			
CO_2 capture in pre-combustion applications			
Develop optimised solvents for CO_2 and H_2S separation			
Develop high cyclic capacity adsorbents with higher selectivity for CO_2 than H_2S			
Develop high-capacity adsorbents for co-separation of CO_2 and H_2S			
Low-temperature separation of CO_2 and H_2			
Develop hydrate-based CO_2 separation			
Develop membrane-based CO_2 separation			
Advance membrane-based H_2 separation			
H_2 gas turbine			
Develop and improve new burner concepts based on dry low NOx burner technology without the need for large amounts of diluents			
Validate numerical design tools for detailed resolution of the fuel/air mixing and combustion			
Develop and test in relevant conditions new cooling technologies, high-temperature materials and hot path coatings			
Integrated components			
Sorption enhanced water-gas-shift: reduce equipment size			
Sorption enhanced reforming/gasification: increase conversion by combining reaction and separation in single units			
Develop chemical looping reforming			
Scale up and reduce costs of membrane water-gas-shift reactors			

	-2020	2020-2030	2030+
Develop stable hydrogen membrane reformers for operation at higher than 500ºC and high pressure with high flux.			
Improve oxygen transport membrane reactors via membrane integration by increasing the surface/volume ratio, increasing lifetime and addressing scale-up issues, while reducing costs.			

Expected impacts for delivery of SET-Plan:

- Sorption-enhanced water-gas-shift and hydrogen membranes ready for demonstration in industrial CCS projects (steel, refineries, hydrogen, biofuels etc.)
- Novel membranes for hydrogen separation and integrated membrane reactors ready for piloting
- Breakthrough processes for H_2 production from fossil fuels (e.g. sorption-enhanced reforming) developed at pilot scale
- Novel high temperature sorbent-based systems for sorption-enhanced reforming.

c) Oxy-fuel

Coal oxy-combustion research has now progressed from lab-scale to full-scale single burner tests – the next step is the large-scale demonstration of oxy-fired coal boilers. Significant progress has also been made in the breakthrough technology, chemical looping combustion (CLC).

	-2020	2020-2030	2030+
Oxygen production for oxy-fuel applications			
Advanced cryogenic air separation employing heat integration with other parts of the power plant, or other adjacent 'cold industries' (e.g. LNG regasification)			
Flexible cryogenic air separation with improved turndown and load-following capabilities with minimised impact on O_2 purity and specific power consumption			
Oxygen-separating membranes (flux, stability, manufacturing)			
Oxygen-separating adsorbents (O_2 capacity, stability)			
Optimised CO_2 purification and compression			
Develop improved membrane and adsorbent material stability for sour conditions			
Develop membrane units, manufacturing, development and process integration			
Oxy-fuel boilers			
Boiler refractories and heat exchanger materials (EA): long-term testing to address issues of slagging, fouling and corrosion related to specific oxy-fuel flue gas conditions			
Sulphur chemistry (EA): investigate formation of various (gaseous) sulphur species (capturing in fly ash, SO_3 formation, reduction of recycled SO_2/SO_3) and direct desulphurisation without intermediate calcination steps			
Lean fuels (low-volatile coals, anthracite, petcoke). Investigate boiler designs in oxy-fuel conditions			
Adapt and validate CFD modelling in oxy-combustion conditions (EA)			
CFB bed material behaviour: improve heat extraction from solid loop, in situ sulphur removal			
Develop and undertake pilot studies of PF and CFB boiler designs for high O_2 concentration: investigate combustion and heat management			
Develop novel pressurised oxy-fuel combustion concepts			
Develop lagging oxy-fuel boilers			
Improve operation with multiple/dirty fuels/biomass in oxy-fuel CFB and co-fired in oxy-fuel PF			
Improve boilers designed for both air-firing and oxy-fuel mode			
Improve oxy-fuel burners for oxy-fuel operation in boilers			

Oxy-fuel gas turbine
Compressor and turbine development for operation with a CO_2/H_2O mixture as working medium
Improve knowledge of heat transfer in CO_2/H_2O mixtures in design of new cooling schemes (EA)
Improve design of process control systems for the semi-closed CO_2/H_2O gas turbine with massive recirculation of the working medium
Develop steam bottoming cycle design to match the gas turbine operating parameters
Investigate oxy-fuel gas turbine combustion of gaseous fuel with O_2 in a CO_2 and H_2O environment under high pressure (EA)
Undertake basic investigation of oxy-fuel gas turbine combustor design in order to enable complete and stable combustion of the fuel under altered (compared to air) heat transfer conditions
Investigate oxygen mixing in the gas turbine process
Develop flameless oxy-fuel combustion
Develop gas turbine designs for both air-firing and oxy-fuel mode
Develop flue gas recycling technologies (materials, components) to ensure safe and efficient operation
Integrated components
CLC O_2 carrier materials (synthetically generated and naturally existing) for gas, coal, biomass or multiple fuels. Investigate existing, oxygen capacity and kinetics, mechanical and chemical stability, toxicity etc.
Develop O_2 carriers for variable fuels (coal, gas, biomass, multiple fuels)
Maximise CLC fuel conversion, including the avoidance of compounds (CO, H_2, CH_4, H_2S) that are not fully converted
Validate and scale up CLC O_2 carrier/ash separation
Low-pressure CLC fluidised bed reactor design, optimisation & scale-up
CLC pressurised reactors: for both coal and gas turbine operation
CLC pressurised packed bed reactors for gas turbine operation
CLC reactor power process integration
Oxygen transport membrane (OTM): materials and reactor development
Integrate new O_2-separation technologies (i.e. membranes and/or adsorbent processes) with oxy-fuel boilers

Expected impacts for delivery of the SET-Plan:

- CLC of natural gas ready for demonstration
- CLC of coal and biomass ready for large-scale piloting
- Packed bed CLC ready for piloting
- Oxy-coal new and retrofit boilers with improved technology ready for full-scale demonstration
- Oxygen transport membranes and oxy-gas turbines ready for piloting
- High-temperature pressurised oxy-combustion, ready for large-scale piloting.

d) Cross-cutting issues and industrial applications beyond power

All three capture routes could, in principle, be adapted to biomass power production and most of the above R&D topics also apply to biomass. Some emerging capture systems (in particular, those operating at high temperature that can combine biomass gasification and/or combustion with CO_2 sorption in a single step) could be especially suited to power plants with biomass and CCS. Both co-firing with fossil fuels and pure biomass applications should be investigated in order to identify the most feasible technology options. If optimised and cost-effective biomass production is achieved, some variants of the technology could be ready before 2030, at the latest. It should also be assessed whether there is any transference of alkalines from the biofuel to the captured CO_2 and if this could imply additional corrosion risks or other issues for CO_2 transport and storage.

For a comprehensive analysis of capture R&D priorities for industrial applications, please refer to ZEP's report: "*Recommendations for research to support CCS deployment in Europe beyond 2020 – Update on CO_2 Capture*".[39]

[39] Annex: web-link

	-2020	2020-2030	2030+
CCS in industrial sectors beyond power: - Study the interaction of the various types of flue gas with the capture solvent - Heat integration - Co-siting and integration with processes other than power plants to increase energy efficiency - The effect of other components and possible contaminants, e.g. hydrogen fluoride			
Develop efficient, flexible CCS technology for natural gas combined cycles and demonstrate load flexibility in future energy systems, also when combined with renewables			
Define agreed process simulation methodologies and benchmark technologies in order to compare the integration of different technologies with common criteria			
European Benchmarking Taskforce: benchmark the effectiveness and capture costs of technologies under development			
Integration of CCS into bioenergy sector (technologies, barriers and potentials) and opportunities for negative CO_2 emission balance in order to accelerate a low-carbon economy			
Dynamic modelling of CO_2 capture processes			
Improved heat exchangers for CCS processes, including materials, heat transfer, manufacturing and modelling			

Expected impacts for delivery of the SET-Plan:

- Advice on which sectors beyond power are most suited for CCS, using which capture technologies
- A uniform methodology for benchmarking capture technologies available for applications in both the short-medium and long-term
- A better understanding of the role that CCS plants can play in energy systems with a high intermittent renewable component.

a) Existing pilots for CO_2 capture

Large-scale capture pilots (50 to 100 tonnes CO_2/day) and demonstration plants (>100 tonnes CO_2/day):

Company	Country	Location	Scale (MW)	Capacity (Tonnes/day)	Technology	Flue gas
Total, Air Liquide and IFPen	France	Lacq	35	200	Oxy-fuel	Gas
E.On	Germany	Wilhelmshaven		70	Post-combustion	Coal
Vattenfall	Germany	Schwarze Pumpe	30		Oxy-fuel	Coal
Enel	Italy	Brindisi		60	Post-combustion	Coal
SOTACARBO	Italy	Carbonia	0.4	6	Pre-combustion (solvents)	Coal
ENEA	Italy	Rome	0.3	4	Pre-combustion (calcium looping)	Coal
Nuon	Netherlands	Buggenum	20		Pre-combustion	Gas
Technology Centre Mongstad	Norway	Mongstad		280	Post-combustion	Gas/coal/industrial
CIUDEN	Spain	Ponferrada	20		Oxy-fuel	Coal
ELCOGAS	Spain	Puertollano	14	96	Pre-combustion	Gas
Vattenfall/SSE	UK	Ferrybridge	5	100	Post-combustion	Coal
RWE Npower	UK	Aberthaw	3.0	50	Post-combustion	Coal

Small- and medium-scale capture pilots (1 to 50 tonnes CO_2/day):

Company	Country	Location	Scale (MW)	Capacity (Tonnes/day)	Technology	Flue gas
TU Wien	Austria	Vienna	0.2		CLC	Gas
EDF, Veolia and Alstom	France	Le Havre		25	Post-combustion	Coal
ENBW	Germany	Heilbronn	0.5	7	Post-combustion	Coal
RWE	Germany	Niederaussem		7	Post-combustion	Coal
IFK	Germany	Stuttgart	0.2		Calcium	Synthetic
TU Darmstadt	Germany	Darmstadt	1.0		Calcium	Coal
TU Darmstadt	Germany	Darmstadt	1.0		CLC	Coal
TNO	Netherlands	Maasvlakte	0.5		Post-combustion	Coal
Hitachi	Netherlands	Nijmegen/Mobile		24	Post-combustion	Gas/coal/industrial
ECN	Netherlands	Petten			Pre-combustion	Synthetic
SINTEF	Norway	Tiller		0.5	Post-combustion	Gas/coal/industrial
AKER Solutions	Norway	Mobile		5	Post-combustion	Gas/coal/industrial
Endesa, Hunosa, CSIC	Spain	La Pereda	1.7		Calcium	Coal
Gas Natural Fenosa	Spain	La Robla	0.3		Calcium	Biomass
Imperial College	UK	London		1	Post-combustion	Synthetic
UKCCSRC-PACT[40]	UK	Sheffield		1	Post-combustion	Coal/gas/liquid fuel/biomass/ synthetic
UKCCSRC-PACT	UK	Sheffield	0.25		Oxy-fuel-FGR	Coal/gas/liquid fuel/biomass
UKCCSRC-PACT	UK	Sheffield	0.33	1	CCGT-HAT	Gas/oil/biofuel
UKCCSRC-PACT	UK	Sheffield	0.33	1	CCGT-EGR	Gas/oil/biofuel

CO_2 transport

	-2020	2020-2030	2030+
Improve understanding of multi-phase flow, including compression			
Develop conceptual design for offshore unloading/injection of CO_2 transport by ship (including compression to, for example, 100 bar)			
Risk assessment for CO_2 pipelines with a focus on cost-efficient mitigation measures and opportunities			
Efficient large-scale infrastructures for CO_2 (cost reduction aspects)			
Cost-efficient and smart design for interim storage to respond to flexibility requirements			
Integrity of large-scale CCS infrastructures: improve understanding of material issues, corrosion, solid formation and interaction of CO_2 on seals for both top-side and down-hole applications. Continued R&D should focus on setting tolerances and re-use of infrastructure.			
Establish an open-access database in order to identify and execute additional thermodynamical properties of CO_2 mixtures, including impurities			
Improve understanding of CO_2 transport leakage scenarios, with special emphasis on cost-efficient mitigation measures			
Assess and propose business models (led by economics research) for regional, multi-user clusters of CO_2 sources. Assess the chain-integration and build-out of the corresponding infrastructure, focusing on connecting the transport of CO_2 from densely populated areas, cross-border issues, operational issues and CCUS.			
Meter technology and meter accuracy to reduce costs			

[40] UK CCS Research Centre – Pilot-Scale Advanced Capture Technology Facilities: www.pact.ac.uk

Expected impacts for delivery of the SET-Plan

- Accelerate the development of CO_2 infrastructure.
- Standardise methodologies and protocols for CO_2 pipeline design and construction.
- Reduce the costs of CO_2 infrastructure.

CO_2 storage

a) Prioritise the development of large storage pilots

For CO_2 storage, the development of large-scale storage pilots is the highest priority in order to build public confidence and finalise regulatory issues. Several sites are required in order to cover different geologies and storage options, on- and offshore: deep saline aquifers, depleted oil and gas fields, and EOR.

Storage pilots have a dual purpose:

1) Prove that CO_2 storage is feasible for the purposes of storage and transport permits, assessment of storage capacity, cost-effective engineering solutions, storage operation, monitoring, injectivity and storage containment, liability transfer and public awareness.
2) Explore and qualify common parameters for a range of deep saline aquifers which project developers can utilise to improve the development of industrial-scale sites.

Results can then be used to improve regulations, identify options for reducing capital and operating costs, assess business cases and contribute to the design of the full value chain.

	-2020	2020-2030	2030+
Urgently establish up to six new CO_2 storage pilots EU-wide (open-access laboratories) to complement CCS demonstration projects: - Undertake a screening study to catalogue existing storage options - Identify research objectives based on previous Framework Programme research and national CCS R&D programmes - Identify CO_2 streams that can be supplied to the storage pilots			

b) Site characterisation

	-2020	2020-2030	2030+
Better understanding and improved coupling of multi-phase flow, thermodynamics, geochemistry and, in particular, geomechanics (including in faults and fractures). Evidence from CO_2 injection operations shows that the geochemistry component is less urgent.			
Quantify the effects of up-scaling on static and dynamic modelling on predictions of storage performance			
Validation of models (calibration, verification and sensitivity analysis of large-scale simulations). A need for real data sets/performance (i.e. at the time data is available from the operation of the storage pilots).			
Benchmarking exercises to compare capabilities of different modelling tools and more clearly define the appropriateness of their application to specific storage issues			
Improve knowledge and predictions of hydraulic properties of faults: - Estimate fault permeabilities, fault development and induced seismicity during CO_2 injection into a fault at realistic depths (at a fault permeability test site) - Study the coupling of geomechanical and geochemical processes, monitoring and remediation technologies			

Expected impacts for delivery of the SET-Plan:

- Improved and systematic estimation of capacity
- Robust and validated predictions of site behaviour
- Validated workflow for site characterisation to meet storage permit requirements.

c) Monitoring

	-2020	2020-2030	2030+
CO_2 plume tracking, leakage detection and quantification at surface (especially offshore), plus pressure development and potable aquifers			
Remote sensing (InSAR, EM etc.) for leakage detection and geomechanical stability			
Biological monitoring for environmental impact assessment			
Continued gathering of offshore baseline data			
Long-term, low-cost monitoring (passive and active) and cost-effective monitoring strategies			
Improved reservoir and over seal monitoring (resolution/sensitivity): - Time-lapse seismic techniques for increased resolution - Micro-seismic design - Monitoring borehole design and down-hole sensors			
Automated statistical procedures to define deviation thresholds in monitoring data sets, compared to baseline (data mining)			

Expected impacts for the delivery of the SET-Plan:

- Definition of baseline and post-injection monitoring requirements
- Improved knowledge of detection thresholds and quantification
- New robust sensors
- More efficient low-cost monitoring tools and strategies
- Validated workflows for typical storage settings.

d) Safe and efficient storage exploitation

	-2020	2020-2030	2030+
Strategies to define the storage complex			
Define key factors (spatial constraints) that affect the interaction of other resources with CO_2 storage/allocation of porespace and resource interaction management			
Test cost-effective engineering solutions (in contrast to demonstration projects where off-the-shelf technologies are expected using lighter equipment). If planned ahead, some high-capex surface facilities could potentially be shared between several pilots.			
Low-cost wells for exploration and observation; low-cost re-completion equipment (e.g. plastic liners) and durable long-life monitoring sensors			
Improved drilling to reduce formation damage and costs			
It is particularly important that operational procedures for deep saline aquifer storage are developed and tested. Integration of the full value chain (including operation of the storage facility) such that CO_2 production facility has maximum availability. Storage optimisation through the development of a range of injection strategies.			
Pressure management, especially for deep saline aquifers, to maximise the storage resource. Understanding pressure responses and pressure management techniques.			
Spatial management of the CO_2 plume – steering, control mechanisms, saturation distribution and re-production of CO_2			
The fate of the CO_2: dissolution, residual trapping and associated time-scales, processes at pore-scale, residual saturation of CO_2 in the pore network, saturation fronts, processes at grain surfaces, impact of wetability and subsequent change. Validate predictions of CO_2-fluid reactions against data obtained at scale in realistic injection and storage scenarios.			
Longer-term trapping: natural CO_2 reservoirs can be used to evaluate the potential for these processes to contribute to long-term site safety cases by constraining predictions of site behaviour with analogue data. Provide reference data sets from natural reservoirs which have been produced for benchmarking predictive simulations and newly acquired monitoring data.			
Improve prediction of geologically controlled CO_2 leakage mechanisms			

	-2020	2020-2030	2030+
Technologies for remediation and mitigation of significant irregularities and leakage			
Gain further experience of the impact of leaked CO_2 on crops etc. as currently studied in the RISCS project			
Remediation testing facility: field-scale tests are needed to demonstrate the effectiveness of technologies for controlling permeability and implementing hydraulic barriers and fluid management to remediate geologically mediated migration for CO_2 storage applications.			
Ecosystem recovery			
Well integrity and flow monitoring facility: gaining experience of the long-term stability of well completion materials			
Well closure and abandonment procedures			
Storage development strategies for early (post-demonstration) deployment			

Expected impacts for delivery of the SET-Plan:

- Definition of risk register
- Practical implementation of the CO_2 storage regulations
- Improved site performance under realistic operating conditions of CO_2 stream compositions and EOR
- National strategies for CCS implementation to meet potentially conflicting demands on pore space and optimise use of storage resources.

e) CO_2 storage projects in Europe

Field	Country	Mt CO_2 stored to date/in total	Storage type	Location
Lacq	France	0.12	Depleted gas field	Onshore
Ketzin	Germany	0.06	Deep saline aquifer	Onshore
K12b	Netherlands	0.06	Depleted gas field	Offshore
Sleipner	Norway	14.00	Deep saline aquifer	Offshore
Snøhvit	Norway	3.00	Deep saline aquifer	Offshore
Hontomín	Spain	0.10[41]	Deep saline aquifer	Onshore

f) Explore the potential of CCUS to advance deployment

	-2020	2020-2030	2030+
Co-optimisation of CO_2 storage and EOR			
Pressure build-up: monitoring and control, water production, combined CO_2 storage and geothermal heat extraction			

[41] Entering operation in October 2013

Annex II: RD&D funding models

The CCS EII has identified a number of innovative funding models which could be used to advance and maximise the benefits of research, demonstration and deployment (RD&D) projects:

- **FP7/Horizon 2020**
  FP7/Horizon 2020 is the EU's primary funding mechanism for achieving the objectives outlined in the SET-Plan. FP7 is being replaced by "Horizon 2020" in 2013, bringing together all existing EU R&D funding, with a proposed total budget of €80 billion. The Horizon 2020 programme has three key pillars:
  - Excellent Science
  - Industrial leadership
  - Societal challenges
- **Increased coordination between Member States**
  Schemes, such as the Berlin funding model and Joint Programming Initiatives (JPIs), aim to initiate stronger action from Member States and other interested countries:
  - Potential project partners from different countries identify a joint research project and present a draft proposal to their respective national funding agencies. This outlines the idea, partners, an estimation and short description of the expected costs (including possible third- party contributions), plus the structure of the project.
  - Upon positive evaluation of the draft proposal by all national funding agencies, project partners submit a full proposal to their national funding agencies, taking into account the alignment of different evaluation procedures in different countries.
  - In the Berlin model, following a positive decision by the national funding agencies, the project partners ask the Commission for additional support that can serve to incentivise collaboration and coordination between partners. Exploitation rights are governed by an agreement among project partners. N.B. The legal basis for the Commission to enter into the Berlin Model has not yet been finalised.
  - Complementing the Berlin model, and typically smaller in volume than Berlin model initiatives, ERA Net+ could be a financing instrument for CCS RD&D whereby a team of willing countries propose competitive calls for topics of mutual interest, e.g. as a pilot for several larger Member State initiatives. This should be made sizeable to allow a greater impact.
- **Direct Member State co-operation without Commission support**
  This is a powerful mechanism that may be executed faster and more efficiently between European countries that wish to develop a joint pilot or demonstration project.
- **Combining R&D funds with EU structural funds**
  New EU financial regulation permits the combination of funding within projects on the condition that funded items are explicitly allocated, or a combination of these funds are used for a portfolio of projects (e.g. a SET-Plan roadmap). The EU is developing guidelines for the period 2014-2020 for Member States and beneficiaries on ways this combination can be achieved using Horizon 2020 and structural funds, which should be published by end 2013.
- **Public-private partnerships**
  Public-private partnerships are an initiative that is funded and operated via a partnership of government and one or more private companies, encouraging collaboration between public and private sectors on CCS R&D, e.g. the UK Energy Technologies Institute includes members such as the UK Government, Shell and Rolls-Royce and executes demonstration projects to progress low-carbon technologies such as CCS.
- **Public underwriting of equity or loans for innovative ventures**
  Implemented by the European Investment Bank (EIB) Group and designed and co-managed by the EU and EIB, the FP7 Risk Sharing Financial Facility (RSFF) offers loans and guarantees to Research, Development and Innovation (RDI) projects and entities. The Commission is considering similar schemes, also including equity components. One such scheme or sub-scheme could target first-of-a-kind demonstration projects.

Annex III: Long-term key performance indicators and targets

The first CCS EII Implementation Plan (2010-2012) included a list of key performance indicators (KPIs) for measuring its success. Its progress is shown in Table 1, where it can be seen that the value of the indicators is still close or equal to that at the start of the Plan. However, this is mainly because they cover a long time span (i.e. longer than the duration of the Plan itself). These KPIs will therefore be maintained in order to ensure continuity and the ability to monitor progress over the long term.

	Metric	Baseline 2010	Targets 2015	Targets 2020	Targets 2025
Overarching KPIs					
Levelised Cost of Electricity (LCoE)					
Coal ref. power plant without (w/o) EUA costs	€/MWh	48.2			
Coal ref. power plant incl. EUA costs	€/MWh	74.8			
Natural Gas (NG) ref. power plant w/o EUA costs	€/MWh	71.9			
NG ref. power plant incl. EUA costs	€/MWh	84			
Coal power plant with CCS, w/o EUA costs	€/MWh	Not applicable (N/a)			72.9
Coal power plant with CCS, incl. EUA costs	€/MWh	N/a			77.9
NG power plant with CCS, w/o EUA costs	€/MWh	N/a			103.5
NG power plant with CCS, incl. EUA costs	€/MWh	N/a			105.6
Cost of CO_2 avoided					
Coal power plant with CCS	€/t (tonne) of CO_2	N/a			37.2
NG power plant with CCS	€/t of CO_2	N/a			109.7
Public awareness of CCS[42]		10% (Eurobarometer survey, 2011)	10% over baseline	20% over baseline	25% over baseline
Demonstration and early commercial CCS projects					
Cumulative FIDs		0	2	5	12
Cumulative number of operated power plant projects		0	0	4	6
Cumulative number of operated industry projects		0	0	1	3
Installed power plant capacity with CCS	MW-gross	0	0	1000	2400
Second-tier KPIs					
Spec. additional CAPEX capture, aggregated average per technology	€/kW-net	N/a			1500
Spec. additional OPEX capture, aggregated average per technology	€/MWh, net	N/a			8
Average plant availability	%, hours/ annum	N/a		74	80
Average CCS chain availability	%, hours/ annum	N/a		74	80
Average plant efficiency	%	N/a		36	38
Average capture rate	%	N/a		85	90
CO_2 stored	Million t/annum	0	0	4.5	11.5
Number of instances of CO_2 movement out of designated containment volume		0	0	0	0
Quantity of CO_2 movement out of designated containment volume	Million t	0	0	0	0
Permits for CO_2 storage		0	3	5	9

Table 1: KPIs for the CCS EII over the long term[43]

[42] CCS EII to check whether Eurobarometer is undertaking surveys during these time periods and the suitability of questions
[43] Costs based on the ZEP cost reports, see page 7

Annex IV: Key actions for the EII Implementation Plan, 2013-2015

Table 2 below shows key actions identified for the second CCS EII Implementation Plan (as listed for each section in Chapter 2).

Section	Key actions	Owner	Timetable
2.1.3	Monitor the progress of the EU CCS demonstration programme and recommend interventions if progress deviates substantially from plan	Joint Research Centre	Report progress at six-monthly intervals
2.1.3	Review mechanisms urgently needed to enable demonstration projects to take FID	ZEP	A paper reviewing support measures needed for demonstration projects to take FID, by November 2013
2.1.3	Assess if support is needed for demonstration projects that have taken FID	CCS EII	Once FID has been taken, contact projects and offer support
2.2.6	Discuss and agree activities for advancing large pilots for both CO_2 capture and storage (lighthouse projects), including cross-cutting activities	ZEP	An action plan to advance lighthouse projects, by end 2013
2.2.6	Discuss and agree activities for advancing long-term R&D activities for second- and third-generation technologies	EERA	Update on an annual basis
2.2.6	Identify funding needs and models for R&D, large pilots and demonstration projects	ZEP/ EERA CCS EII	- ZEP to prepare a proposal for funding R&D, large pilots and demonstration projects (via new and existing models), by end 2013 - CCS EII to develop a plan for implementing funding models for CCS, by June 2014
2.2.6	Support the development of natural gas CCS and demonstrate its load flexibility in future energy systems, also when combined with renewables	EERA	A paper, including a recommendation for a relevant call in Horizon 2020, by Q1 2014
2.2.6	Promote and review proposals to utilise clustered on-/offshore storage options	Research Council of Norway	A report reviewing proposals for clustered storage, by Q1 2014
2.2.6	Support development of CCS in industrial applications and their integration into transport/storage infrastructure clusters	ZEP	- A paper on actions needed to support the development of industrial applications for CCS, based on ZEP's report, by end Q3 2013 - Record and report the number of industrial applications per year
2.2.6	Support the integration of biomass/municipal wastes in the CCS chain and the integration of biogenic CO_2 sources into transport/storage infrastructure clusters	ZEP	Facilitate the Commission in setting up a call for proposals under Horizon 2020 on Bio-CCS, by Q4 2014, with a view to addressing issues raised by the EBTP/ZEP Bio-CCS report[24]
2.2.6	Explore the potential for CCUS projects to advance CCS deployment	ZEP	A position paper on the role of CCUS, by end Q3 2013

Section	Key action	Owner	Timetable
2.3.3	Review mechanisms urgently needed to keep CCS on track to achieve EU climate goals	ZEP	A paper reviewing mechanisms needed to keep CCS on track to achieve EU climate goals, by end 2013
2.3.3	Provide feedback on the review of the CCS Directive in 2015	ZEP	A paper reviewing the CCS Directive, by end 2013
2.3.3	Develop effective business models for CO_2 transport and storage infrastructure	ZEP	A position paper on the development of effective business models for CO_2 transport and storage infrastructure, by end Q1 2014
2.3.3.	Review policy measures underway to achieve EU climate goals	European Commission	Report status at each CCS EII meeting
2.3.3	Raise awareness of the urgent need to reward negative emissions via the capture and storage of biogenic CO_2 under the EU ETS	ZEP	Position paper on the importance of rewarding negative emissions under the EU ETS, by Q1 2014
2.4.2	Identify and, where appropriate, facilitate the implementation of measures to increase public and political awareness and support for CCS	NGOs	Assessment of impact of CCS communications activities in key areas (e.g. online), by end Q2 2014
2.4.2	Assess the suitability of launching a call for academics and other institutions to submit papers on the societal and economic impacts of CCS	NGOs	Assessment to be completed by end Q2 2014
2.5.1	Monitor the number of demonstration projects in the CCS Project Network and new international knowledge sharing initiatives and provide guidance, as appropriate; support knowledge sharing between demonstration projects and large R&D pilots; and in general, between industry and the R&D community	CCS EII	Report status at each CCS EII meeting
2.5.1	Encourage industry, the Commission and Member States to continue to grow CCS networks internationally through bilateral initiatives and forums such as the Carbon Sequestration Leadership Forum, IEA, Clean Energy Ministerial and GCCSI, including engagement and joint activities with developing countries	CCS EII	Report status at each CCS EII meeting
2.5.1	Continue and intensify a regular information exchange on national CCS R&D activities aimed at synchronising all relevant Member State research programmes; also involve international organisations in order to include non-European CCS R&D activities	CCS EII	Report status at each CCS EII meeting
2.5.1	Ensure that CCS applications in industries beyond the power sector are included in any relevant knowledge sharing and exchange processes	CCS EII	Report status at each CCS EII meeting

Table 2: Key actions and timetable for the CCS EII Implementation Plan, 2013-2015