Zero emissions platform

Recommendations for research to support CCS deployment in Europe beyond 2020

Update on CO_2 Capture

European Technology Platform for Zero Emission Fossil Fuel Power Plants

Contents

1 Introduction

The critical role of CO_2 Capture and Storage (CCS) in meeting the EU's energy, climate and societal goals is now indisputable: the European Commission's Communication[1] *on CCS has confirmed that is not only "vital for meeting the Union's greenhouse gas reduction targets", it provides a "very visible link between jobs in local communities and continued industrial production". Indeed, CCS must account for 19-32% of total emissions reductions in the power sector by 2050, which means that "For all fossil fuels, Carbon Capture and Storage will have to be applied from around 2030 onwards".* [2]

In 2010, ZEP published its ground-breaking report, "Recommendations for research to support the deployment of CCS in Europe beyond 2020"[3] which identified the main R&D areas for driving down costs through well-targeted R&D programmes. FP7-ENERGY calls have taken into account several of the recommended priorities, developing various key components of the CCS value chain.

Ongoing R&D for CCS is essential in order to drive down costs – and deliver EU climate targets

In the power sector, first-generation technologies for all three capture pathways (post-combustion, pre-combustion and oxy-fuel) have already been tested at large pilot-scale facilities and are now ready for the demonstration phase. However, CO_2 capture is an emerging technology and historical experience with comparable processes suggests that significant improvements are achievable through futher well-targeted R&D. The optimisation of current and next-generation technologies is therefore essential to further drive down costs, enable rapid deployment post 2020 – and deliver EU climate targets.

R&D is also needed to validate capture technologies for use in industries *beyond* power – expected to deliver half of the global emissions reductions required by 2050 from CCS.[4] Indeed, in some industries, such as steel and cement, it is the only means of achieving deep emission cuts. As several have almost pure CO_2 streams, this also dramatically reduces the cost of CO_2 capture, while clustering different CO_2 sources to a transport network will result in significant economies of scale for both industrial *and* power projects.

Combined with sustainable biomass, CCS can even remove CO_2 from the atmosphere (Bio-CCS[5]) – the only large-scale technology that can deliver net *negative* emissions (in addition to any emissions reductions achieved by replacing fossil fuels with biomass). Certain biofuels production routes could provide 'low-hanging fruits' for early, low-cost CCS deployment and in the US, Bio-CCS is already being deployed at industrial scale.[6]

This report therefore prioritises immediate R&D needs of CO_2 capture, focusing mainly on the power sector, while identifying the need to verify industrial applications – taking into account advances achieved to date and future requirements to drive down costs.

Future R&D programmes must also allow for new, breakthrough technologies

While long-term R&D needs have been identified for CO_2 capture technologies known today, novel technologies – or the novel use of known technologies – are likely to be presented in the years to come. It is therefore vital that future R&D programmes are formulated in such a way that breakthrough technologies can be incorporated and given a fair evaluation.

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[1] http://ec.europa.eu/energy/coal/ccs_en.htm
[2] http://ec.europa.eu/energy/energy2020/roadmap/doc/com_2011_8852_en.pdf
[3] www.zeroemissionsplatform.eu/zep-long-tem-r-d-ccs
[4] International Energy Agency (IEA). See also ZEP's report, "CO_2 Capture and Storage (CCS) in energy-intensive industries: an indispensable route to an EU low-carbon economy": www.zeroemissionsplatform.eu/library/publication/222-ccsotherind.html
[5] See ZEP's report, "Biomass with CO_2 Capture and Storage (Bio-CCS) – The way forward for Europe": www.zeroemissionsplatform.eu/library/publication/206-biomass-with-co2-capture-and-storage-bio-ccs- the-way-forward-for-europe.html
[6] The ADM bioethanol-CCS project

Such technologies must not only be advanced and innovative, but have the potential to effect improvements compared to first-generation technologies – mainly in terms of cost and efficiency. They will then have to undergo the full development product cycle (laboratory – small/large pilot – demonstration – pre-commercial (first-of-a-kind) – commercial). Finally, it is essential to recognise the need for large-scale pilots, which are risky and costly to carry out and therefore a limiting factor for new developments.

ZEP will also publish an update on research priorities for CO_2 transport and storage in due course.

The Zero Emissions Platform (ZEP)

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

This report has been developed by CO_2 capture experts within ZEP's Taskforce Technology (Working Group (WG) 'Long-term R&D Plan for Capture Technology', with additional contributions from WG 'Other Industries').

www.zeroemissionsplatform.eu

2 Recommendations for research on CO_2 capture

2.1 Technology structure and evaluation methodology

Sections 2.2-2.5 contain an overview of technologies that could be applicable to CO_2 capture from power plants, or enable the potential of CO_2 capture to be fully realised. The technologies have been structured according to the technology blocks in section 2.1.2. Development of technology maturity over time has been estimated for three periods (see section 2.1.1, Definition of timeframe) and maturity levels defined (see section 2.1.3, Definition of validation status). It must be emphasised that the estimated development of technology maturity depends on continuous R&D in the identified areas.

However, a multitude of R&D topics has been identified in this report and pursuing R&D in all areas would be very costly. Research carried out over the past decade has enabled a tremendous increase in knowledge of CO_2 capture from power plants, which enables the identification of some technologies as more promising than others. It is also recognised that there are many technologies where it is still too early to quantify what kind of impact they will have on CO_2 capture, since more R&D is still required.

Based on experience within ZEP, an evaluation has therefore been made of whether the R&D topics listed could have a positive impact on investment decisions by power plant operators. The methodology applied is described in section 2.1.4 and the resulting recommendations for further research on CO_2 capture provided in section 2.6. It should be noted that some of the technologies listed in sections 2.2-2.5 are not explicitly recommended for further R&D by ZEP, but are still included for the sake of completeness.

2.1.1 Definition of timeframe

The timeframe for long-term R&D has been categorised for the following intervals, corresponding to periods where R&D efforts performed now and in the years to come will result in commercially available technologies:

- *Period I, up to 2020*: short term – not the subject of this report, but provided in order to establish a baseline and likely development. Investment decisions made in the early 2020s will need some proof of concept and must therefore be based on technologies that are fully validated (green in summary tables – see section 2.1.3) during Period I or early in Period II.
- *Period II, 2020-2030*: technologies brought to commercial operation within this period are likely to be based on improvements and refinements of technologies employed in Period I. Some new technologies, today in the R&D phase, should reach the demonstration or even the commercial phase.
- *Period III, 2030 and beyond*: long-term technologies – technologies brought to commercial operation within this period are likely to be based on optimised and refined technologies from Periods I and II. In particular, demonstration phase technologies from Period II should become commercial. New technologies, which today could be in R&D infancy, should reach the demonstration phase and then become commercially available.

2.1.2 Capture routes and technology blocks

Table 1 below gives an overview of the "technology blocks" within each of the three main capture routes, in accordance with ZEP's "Matrix of Technologies[7]" (October 2008), although the structure has been slightly rearranged. Technology blocks that are specific to CO_2 capture are in **bold** and the long-term R&D needs for these blocks are further described in chapters 2.2 to 2.4. Technology blocks that are not directly linked to only one CO_2 capture technology (e.g. 'CO_2 compression') are not in bold in Table 1 and are addressed in chapter 2.5. This is also the case for technology blocks that are not CO_2 capture specific but more generally related to power plant improvements (e.g. 700°C steam cycle).

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[7] www.zero-emissionplatform.eu/website/docs/ETP%20ZEP/ZEP%20Technology%20Matrix.pdf

Table 1: CO_2 capture technology blocks (according to ZEP's document: "CO_2 Capture and Storage (CCS) – Matrix of Technologies"[6]):

<table>
<tr><td colspan="2">Post-combustion</td><td colspan="2">Oxy-fuel</td><td>Pre-combustion</td></tr>
<tr><td colspan="2"></td><td colspan="2">Oxygen separation</td><td>Oxygen separation</td></tr>
<tr><td colspan="2">Fuel preparation
Lignite drying</td><td colspan="2">Fuel preparation
Lignite drying</td><td>Fuel handling
Lignite drying</td></tr>
<tr><td colspan="2">Combustion (NG GT, Coal PC, Lignite PC, CFB, Biomass)</td><td colspan="2">Oxy-combustion (Oxy-PC/ CFB, Oxy-gas, Biomass)</td><td>Gasification/reforming (NG, Coal, Lignite, Biomass)</td></tr>
<tr><td>Boiler</td><td>Gas turbine</td><td>Boiler</td><td>Gas turbine</td><td>Dust removal</td></tr>
<tr><td colspan="2">Steam cycle</td><td colspan="2">Steam cycle</td><td>Water-gas shift</td></tr>
<tr><td>700°C cycle.</td><td></td><td>700°C cycle.</td><td></td><td></td></tr>
<tr><td></td><td>CO_2 enrichment in flue gas</td><td colspan="2">Flue gas recycling and O_2 mixing</td><td>Desulphurisation</td></tr>
<tr><td colspan="2">Flue gas treatment and heat recovery</td><td colspan="2">Flue gas treatment and cooling</td><td>CO_2 capture/H_2 separation</td></tr>
<tr><td colspan="2">CO_2 capture</td><td colspan="2"></td><td>H_2 gas turbine</td></tr>
<tr><td colspan="2">CO_2 purification*</td><td colspan="2">CO_2 purification</td><td>CO_2 purification*</td></tr>
<tr><td colspan="2">CO_2 compression</td><td colspan="2">CO_2 compression</td><td>CO_2 compression</td></tr>
<tr><td colspan="2"></td><td colspan="2">Integrated components **</td><td>Integrated components **</td></tr>
<tr><td colspan="2">Overall process development and integration</td><td colspan="2">Overall process development and integration</td><td>Overall process development and integration</td></tr>
</table>

* For processes where the CO_2 stream formed contains co-adsorbates and/or other impurities that cannot be sequestrated with the CO_2, further processing will be necessary. Specific separation steps addressing this may therefore give rise to R&D activities where the aim is to modify existing processes or develop new specific separation processes.

** Two or more components/sub-processes integrated into one unit. Examples are CLC in the oxy-fuel route combining oxygen separation and combustion, and sorption enhanced reforming/gasification in the pre-combustion route combining gasification/reforming, water-gas shift and CO_2 removal.

2.1.3 Definition of validation status

In the following chapters, summary tables are provided where colour coding defines the validation status of the different technologies under each technology block. As in ZEP's "Matrix of Technologies"[6], validation status is divided into three levels:

- **Red** Not validated: not tested/less advanced than pilot scale
- **Yellow** Partly validated: ready for a demonstration plant (a few 100s of MW_{el}, depending on the technology)
- **Green** Fully validated: commercially available for application in large power plants.

2.1.4 Methodology for evaluating the importance of R&D topics

In order to evaluate the importance of R&D topics listed, an estimate was made of the impact of each R&D topic on various investment decision parameters *if/when the technology researched becomes fully validated and ready for commercial applications* (validation status Green, as defined in section 2.1.3). As far as possible, this has been assessed with reference to appropriate base cases consisting of present commercially available technology.

Seven investment decision parameters were defined (Table 2) for which different weighting factors were assigned in order to rank them according to typical power plant operator priorities when making investment decisions. The weighting factors therefore also provide guidance on the relative importance of areas in the search for improvements in CO_2 capture-related technologies.

Table 2: Definitions and weighting factors for investment decision parameters used to assess the impact of R&D topics on commercialised CO_2 capture.

Investment decision parameter	**Weighting factor**	**Definition**
Efficiency	2	Impact of the technology on the electric efficiency of the power plant
CAPEX	2	Capital expenditures, i.e. impact of the technology on investment costs for the power plant
O&M (excluding fuel)	1.5	Impact of the technology on operational and maintenance costs of the power plant, excluding fuel costs which are covered by the efficiency parameter. This can include costs incurred by (e.g.) solvent replacement or membrane replacement.
Availability	1.5	Impact of the technology on the availability of the power plant. The availability of a power plant is the percentage of time over one year that the plant is capable of producing electricity and includes both planned and unplanned stops.
Operability	1.5	Impact of the technology on the operability of the plant, i.e. on flexibility (acceptable steady-state operation over a range of conditions), controllability (ability to move to new steady-state set-points and to handle process disturbances), start-up/shutdown characteristics and the ability to handle equipment failures in a safe manner.[8]
HSE	1	Impact of the technology on health, safety and environment (HSE) related to the power plant operation
Capture rate	1	The fraction of the CO_2 generated by the power plant that is captured (90% CO_2 capture is the base case).

[8] Alie, C., Douglas, P. L., Davison, J. On the operability of power plants with CO_2 capture and storage, Energy Procedia 1 (2009) 1521-1526.

Motivation for assigned weighting factors
When a decision is made whether to invest in a new power plant, efficiency and CAPEX are generally the two most important parameters, since these are decisive for the economy of the power plant over its lifetime. This justifies a weighting factor of 2. The costs of operation and maintenance are also important for investment decisions, although not as important as CAPEX, which justifies a weighting factor of 1.5.

Furthermore, it is predicted in the EU Energy Roadmap 2050 that the share of renewable energy will rise substantially in Europe until 2050. A significant share of renewables in the power system will pose large requirements on balancing power that can be rapidly put into operation when renewables such as wind or solar power are not producing electricity. This, in turn, means that the operability of power plants with CO_2 capture may become an important basis for investment decisions in the future. However, the owner's requirements on load-changing capacities could very well vary for different power plant concepts, e.g. an IGCC is likely to operate in base load, where as an NGCC is more likely to have a load following role. Altogether, the importance of power plant operability justifies a weighting factor of 1.5.

The availability of power plants, i.e. the amount of time during a year that they can actually produce power, is also important when making investment decisions; and the same importance is assigned to operation and maintenance costs, excluding fuel (which is covered by the efficiency parameter). Altogether, these two parameters justify a weighting factor of 1.5.

Hence, the two remaining technology parameters with the lowest weighting factors are HSE and CO_2 capture rate. HSE can be regarded as a binary issue that needs no further weighting. Significantly increased negative impact on HSE from a CO_2 capture technology under development is enough to halt this technology, regardless of potential improvements in efficiency and CAPEX. Improvements in HSE can also be an additional reason for pursuing an R&D topic that appears fairly promising.

Assigning a weighting factor of unity to CO_2 capture rate is justified by the fact that the baseline capture rate considered for the R&D topic evaluation is 90%. There are certainly technologies available which can increase CO_2 capture rate beyond 90%, but it is usually possible to design the overall power plant in such a way that efficiency is increased and/or CAPEX reduced, while targeting 90% CO_2 capture. Technologies that achieve a CO_2 capture rate significantly below 90% will also, in an appropriate economical context, be penalised through increased O&M costs due to high CO_2 emissions.

Enabling activities
It is not relevant to evaluate some of the R&D topics listed in section 2.2-2.5 against the technology parameters listed in Table 2. Typical examples are the development of numerical simulation tools or materials databases. The purpose of this category of R&D topics is to enable an improved capture route, rather than achieve a direct technology improvement. (Enabling activities are marked “EA” in the summary tables in sections 2.2-2.5).

It must be emphasised that the conclusions and recommendations in section 2.6 are based on *estimates* of the impact of different R&D topics, according to the current level of knowledge within ZEP. The level of knowledge is also different for different parameters, with the greatest knowledge available for efficiency, capture rate and CAPEX, which are generally the research areas first explored for a novel technology. Operability and availability are still, to a large extent, unexplored research areas.

2.2 Post-combustion technologies

2.2.1 CO_2 capture in post-combustion applications

Post-combustion capture technologies can, in principle, be applied to flue gases from all kinds of industrial processes, in particular power production from fossil fuels and biomass, cement, steel and aluminium production. Several separation principles are relevant. Absorption based on liquid chemical solvents (amines) is currently the leading and most developed technology. Further along the timeline, high temperature calcium looping cycles, which have undergone a fast development process in recent years, is seen as a potential candidate; also membrane separation and adsorption by low temperature solid sorbents are potential candidates in the longer term.

Key challenges and long-term R&D targets

- Flexible operation of integrated capture and power plants.
  Long-term R&D target: develop processes that enable the integrated plant to respond quickly and efficiently to changes in power and carbon markets.
- The high energy requirement of the separation process; a penalty of ~10% points in efficiency loss with present technology (MEA). A long-term R&D target (beyond 2030) should be to reduce this to below 5% points.
- The low CO_2 partial pressure (especially for NG power plants) and the large flue gas volumes imply very large equipment volumes and contacting surfaces.
  Long-term R&D target: reduce equipment volumes by developing more effective contacting surfaces.
- Flue gas impurities (depending on fuel).
  Long-term R&D target: develop capture processes independent from, or at least very robust with respect to composition of impurities in the flue gas. Develop capture processes which can efficiently co-capture impurities of larger concentration (e.g. SO_2).
- Degradation and environmental aspects.
  Long-term R&D target: develop processes with very low overall emission levels (e.g. degradation products) and in line measurement techniques for very low concentrations.
- Material of construction
  Long-term R&D target: develop lower cost materials for construction of capture plants.

R&D needs

- Liquid absorbents: liquid solvents need to have a lower energy requirement for regeneration than today, be non-toxic and environmentally friendly. They should also be robust against flue gas impurities and have a low degradation rate. In order to decrease CAPEX and OPEX, technological development of gas/liquid contactors is also necessary (including also membrane contactors). Research on this type of solvent is ongoing and progressing, but is likely to continue beyond 2020. Systems using additional effects such as precipitation, pH swing and liquid extraction will probably play an important part in their development. Adaptation of capture and power process configurations is also necessary to make best use of these improved solvents.
- Calcium looping (or carbonate looping) is a chemical looping type of process that uses CaO particles to react with CO_2 in the flue gas. In recent years, this process has reached MW_{th} pilot scale, using existing Circulating Fluidised Bed technology in the carbonator reactor. The subsequent calcination of $CaCO_3$ in an oxyfired CFBC (see 2.3.2) regenerates the CaO and returns CO_2. The overall efficiency penalty can approach 6% points. R&D issues are: scaling up of Circulating Fluidised Bed carbonator and experimental validation at increasing scales, alternative calciner designs, CO_2 sorbent performance issues related to chemical and mechanical stability, integration of purge uses, combined SO_2 capture and low-cost reactivation processes.
- High-temperature solid sorbents other than natural CaO/CaCO3.
- Low-temperature solid sorbent (amines supported on carbon, metal oxide frameworks etc.) are being investigated as alternative functional materials for post-combustion CO_2 capture. High adsorption rates, selectivities and capacities under low partial pressures of CO_2 are needed for these materials to be suitable for large-scale CO_2 capture.
- Membranes: the application of membranes in fossil fuel power plants requires large membranes that can be maintained and repaired. They also have to withstand pollution, fouling, as well as temperature

and pressure changes – properties that cannot be delivered by today's membrane technology. R&D needs: development of low-cost and more robust membrane modules with high permeability and selectivity.

- Cryogenic technologies: cryogenic liquefaction is feasible today, anti-sublimation process for CO_2 separation is in the early demonstration phase.
- Generating hydrates for CO_2 capture: R&D is needed to increase selectivity and kinetics.
- Materials of construction: R&D for lower-cost solutions.

Summary table: post-combustion CO_2 capture

(Colour codes: Green – validated, Yellow – partly validated, Red – not validated)

	-2020	2020-2030	2030-
Liquid solvents, energy requirement < 2.5 GJ/tonne CO_2	[Yellow]	[Green]	[Green]
Liquid solvents, energy requirement < 1.5 GJ/tonne CO_2	[Red]	[Red / Yellow]	[Green]
Minimisation of solvent degradation/avoidance 7of emissions*	--	--	--
Calcium looping (a.k.a carbonate looping)	[Yellow]	[Yellow / Green]	[Green]
High-temperature solid sorbents other than natural CaO/CaCO3	[Red / Yellow]	[Yellow]	[Green]
Low-temperature solid sorbents	[Red / Yellow]	[Yellow]	[Green]
Capture processes for liquid and solid sorbents* (EA)	--	--	--
Membranes development and stability	[Red]	[Yellow]	[Green]
Cryogenics: anti-sublimation	[Yellow]	[Green]	[Green]
Hydrates	[Red]	[Yellow]	[Green]

*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

2.2.2 CO_2 enrichment in flue gas from gas turbines

The basic idea with this concept is to recirculate part of the flue gas from the gas turbine back to the compressor inlet, thereby increasing the CO_2 concentration in the flue gas, which is beneficial to the post-combustion CO_2 capture process. Concepts with oxygen-enriched air are also envisaged for producing flue gases with a further increase in CO_2 concentration.

Key challenges and long-term R&D targets

- Increase CO_2 content in the flue gas in order to facilitate CO_2 capture.
- Stable and complete combustion in CO_2- and/or oxygen-enriched atmosphere

R&D needs

- Process configuration optimisation with recirculation of (part of) the flue gas prior to the CO_2 capture unit
- Adaptation of gas turbines for operation with new CO_2- and/or oxygen-enriched media, in particular to ensure stable and complete combustion

Summary table: CO_2 enrichment in flue gas

(Colour codes: Green – validated, Yellow – partly validated, Red – not validated)

	-2020	2020-2030	2030-
Process configuration optimisation	[Yellow]	[Green]	[Green]
Gas turbine development for CO_2 and/or O_2 enrichment	[Red]	[Yellow / Green]	[Green]

2.2.3 Overall process development and integration

Integration of the post-combustion capture process with the power generation process and CO_2 compression is a key issue for reducing the energy penalty of post-combustion capture and therefore requires further attention. Overall environmentally-friendly integration of the power plant with respect to water consumption and pollutants is also vital.

Key challenges and long-term R&D targets

- Development of gas and solid fuel power processes with integrated post-combustion CO_2 capture process, with maximised power output and minimum loss of waste heat, also taking into account good part-load performance.

R&D needs

- Minimisation of overall energy penalty for flue gas cleaning and CO_2 compression and intercooling
- Minimisation of overall energy penalty for the steam cycle configuration with respect to CO_2 capture and compression, and good part-load performance
- Impact of integration on system reliability and availability
- Environmental integration of the power plant with respect to (e.g.) cooling water requirements, liquid effluents and their purifications
- Development and implementation of dynamic models to study transients in the power process, as well as in the capture unit

Summary table: overall process development and integration

(Colour codes: Green – validated, Yellow – partly validated, Red – not validated)

	-2020	2020-2030	2030-
Energy efficient flue gas cleaning and CO_2 compression	Yellow	Green	Green
Optimisation of steam power cycle to match capture process*	--	--	--
Integration impact on reliability and availability *	--	--	--
Environmental integration of power plant*	--	--	--
Dynamic modelling, simulations and analysis*	--	--	--

*Maturity depends on the capture process under consideration

2.3 Oxy-fuel technologies

2.3.1 Oxygen production for oxy-fuel applications

For the first large-scale demonstrations (100s of MW_{th}) of oxy-fuel power plants and the first commercial generations, cryogenic air separation will be the only viable air separation technology at large scale. In the longer term, other air separation technologies based on membranes or adsorbents are seen as potential candidates.

Key challenges and long-term R&D targets

- Reduced energy consumption for oxygen production. Specific energy consumption of current cryogenic processes is in the range of 160-220 kWh/tonne at ISO conditions.[9] A long-term R&D target is to reduce this to 120-140 kWh/tonne for improved cryogenic processes and to 90-120 for membrane or sorbent-based technologies.
- Standardisation to reduce investment costs for cryogenic ASUs
- Adaption and optimisation of cryogenic air separation for specific oxy-fuel boiler requirements.

[9] Air at 101325 Pa, 15°C, 60%RH and oxygen at atmospheric pressure; for oxygen at 140 kPa abs, it adds 10 kWh/tonne

R&D needs

- Advanced cryogenic air separation technology, 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
- High-temperature oxygen-separating membranes and adsorbents which may have the potential for efficiency improvement in oxy-fuel operation, compared to cryogenic ASU
  - Further materials development (flux, improved performance at lower temperatures (below 700°C), industrial fabrication methods)
  - Materials stability at sour conditions (enables use of recycled CO_2 for sweep/regeneration)
  - Further component development (membrane scale-up and manufacturing and adsorbent reactor design) and integration into the power process
  - Pilot and full-scale demonstration.

Summary table: oxygen production for oxy-fuel applications

(Colour codes: Green – validated, Yellow – partly validated, Red – not validated)

	-2020	2020-2030	2030-
Advanced cryogenic air separation			
Flexible cryogenic air separation			
Oxygen separating membranes (flux, stability, manufacturing)			
Oxygen separating adsorbents (O2 capacity, stability)			
Membrane and adsorbent material stability at sour conditions			
Membrane unit manufacturing, development and process integration			
Adsorbent unit development and process integration			

2.3.2 Oxy-fuel boilers

In Period I, extensive R&D is ongoing to create a strong, validated basis for the design of oxy-fuel boilers for use in large-scale demonstrations of oxy-fuel power plants (100s of MW_{th}). Validations and R&D are also expected to continue beyond the first demonstration plants. These first generation(s) of oxy-fuel boilers will operate at conditions similar to air-fired boilers. Selecting a higher O_2 concentration for PF, as well as CFB boilers, provides the potential for cost savings and efficiency improvements, but also requires completely new boiler designs.

Key challenges and long-term R&D targets

- In Period I, R&D on corrosion, slagging and fouling in solid fuel oxy-fuel PF and CFB boilers is ongoing and expected to continue beyond the first demonstration plants.
- Exploit the inherent potential for boiler size and cost reduction for PF and CFBs by enabling higher O_2 concentrations and thus reduced flue gas recirculation.
- Improved knowledge of sulphur chemistry for solid fuels
- Enhanced knowledge of the use of lean fuels (low-volatile coals, anthracite, petcoke)
- In Period I, improved CFD modelling is ongoing and expected to continue beyond the first demonstration plants.

R&D needs

- Boiler heat exchanger and refractory materials: issues regarding slagging, fouling and corrosion related to specific oxy-fuel flue gas conditions need further investigation; tests are ongoing and expected to continue beyond the first demonstration plants.

- Formation of various (gaseous) sulphur species (capturing in fly ash, SO_3 formation, reduction of recycled SO_2/SO_3) and direct desulphurisation without the intermediate calcination step to be further investigated.
- Lean fuels (low-volatile coals, anthracite, petcoke) require special furnaces (down-shot, slag-tap) and/or special combustion technologies (indirect firing) for air combustion. Oxygen enrichment may offer the application of conventional direct PF combustion in conventionally shaped furnaces.
- CFD modelling (chemistry, interaction with CO_2, radiation) is being adapted for oxy-combustion and validated in Period I, and expected to continue beyond the first demonstration plants.
- CFB bed material behaviour: heat extraction from solid loop, in-situ sulphur removal is being investigated in Period I.
- PF and CFB boiler design for size and cost reduction with increased O_2 concentration (i.e. less flue gas recycled). The development and tests in laboratory and pilot plants of:
    - Combustion characteristics in high O_2 concentration
    - Design and heat managing schemes for high O_2 concentration boilers
- Novel pressurised combustion concepts (with dry or wet coal feed) able to produce a concentrated, pressurised CO_2 stream
- Slagging oxy-fuel boilers
- Operation with multiple/'dirty' fuels/biomass in oxy-fuel CFB and co-fired in oxy-fuel PF
- Development and optimisation of boilers that can switch between air-firing mode and oxy-fuel mode
- Development and optimisation of burners for oxy-fuel operation in boilers.

Summary table: oxy-fuel boilers

(Colour codes: Green – validated, Yellow – partly validated, Red – not validated)

	-2020	2020-2030	2030-
Boiler refractories and heat exchanger materials (EA)			
Sulphur chemistry (EA)			
Lean fuels (low-volatile coals, anthracite, petcoke)			
CFD Modelling (EA)			
CFB bed material behaviour			
High O_2 concentration combustion, heat management			
Pressurised oxy-fuel combustion concepts			
Slagging oxy-fuel boilers			
Multiple/dirty fuels/biomass in CFB			
Boilers designed for both air-firing and oxy-fuel mode			
Oxy-fuel burners			

2.3.3 Oxy-fuel gas turbine

The natural gas-fired oxy-fuel gas turbine, operating with a CO_2/H_2O mixture as the working medium, and with recirculation of the main part of the working medium, can be designed from an aerodynamic point of view within current engineering practice. R&D is still needed in terms of structural analysis and materials to be used for construction, also taking the altered heat transfer conditions into account.

Key challenges and long-term R&D targets

- Turbomachinery development, taking into account the altered heat transfer conditions in the hot parts
- Overall process design and control
- Oxy-fuel gas turbine combustors: combustion and heat transfer

R&D needs

- Design of compressor and turbine for operation with a CO_2/H_2O mixture as the working medium
- Improved knowledge of heat transfer in turbines operating with a CO_2/H_2O mixture, for the design of new cooling schemes
- Design of control system for the semi-closed CO_2/H_2O gas turbine, with massive recirculation of the working medium
- Development of steam bottoming cycle to match the gas turbine operating parameters
- Oxy-fuel gas turbine combustors:
  - Basic investigation of combustion of gaseous fuel with O_2 in a CO_2 and H_2O environment under high pressure
  - Combustor design to enable complete and stable combustion of the fuel under altered (compared to air) heat transfer conditions
- Investigation of oxygen mixing in the gas turbine process
- Flameless oxy-fuel combustion
- Gas turbine design with the flexibility to switch between air-firing and oxy-fuel mode

Summary table: oxy-fuel gas turbine

(Colour codes: Green – validated, Yellow – partly validated, Red – not validated)

	-2020	2020-2030	2030-
Compressor and turbine development	Yellow	Yellow / Green	Green
Heat transfer in CO_2/H_2O mixtures (EA)	Yellow	Yellow / Green	Green
Process control	Yellow	Yellow / Green	Green
Steam bottoming cycle design	Yellow / Green	Green	Green
Oxy-fuel gas turbine combustion basics (EA)	Yellow	Yellow / Green	Green
Oxy-fuel gas turbine combustor design	Red	Yellow / Green	Green
Oxygen mixing in gas turbine plant	Yellow	Yellow / Green	Green
Flameless oxy-fuel combustion	Yellow	Yellow / Green	Green
Gas turbines designed for both air-firing and oxy-fuel mode	Red	Yellow	Green

2.3.4 Flue gas recycling and O_2 mixing

Systems for mixing oxygen and recycled flue gases are being investigated and tested in Period I. Further improvements can be beneficial for combustion process control.

Key challenges and long-term R&D targets

- Technologies and approved construction materials for the safe mixing of oxygen and recycled flue gases that may contain dust and unburnt carbon
- Individual mixing points for O_2 and recirculated flue gas (in burner, overfire, pulveriser)

R&D needs

- Research and validation of technologies and approved construction materials for safe mixing of recycled flue gases and oxygen is ongoing in Period I and expected to continue.
- Individual mixing of O_2 and recirculated flue gas may offer further possibilities to steer the ignition/ pyrolysis/combustion process.

Summary table: flue gas recycling and O_2 mixing

(Colour codes: Green – validated, Yellow – partly validated, Red – not validated)

	-2020	2020-2030	2030-
Safe mixing of recycled flue gases and oxygen (EA)			
Individual mixing of O_2 and recirculated flue gas			

2.3.5 Flue gas treatment and cooling

R&D to adapt and validate by-product handling for specific oxy-fuel flue gas conditions is ongoing in Period I and further improvements are expected beyond this period.

Key challenges and long-term R&D targets

- Improved handling of by-products in the oxy-fuel generated CO_2 stream

R&D needs

- Overall optimisation of NOx removal in the entire capture chain is necessary to consider overall removal efficiency and costs from upstream flue gas cleaning or downstream CO_2 compression processes, or a combination of both options.
- Emission control from air-firing to oxy-fuel combustion could be a topic for flue gas cleaning design and operation.
- Selective Catalytic Reduction (SCR), Selective Non-Catalytic Reduction (SNCR) for DeNOx: due to specific oxy-fuel flue gas conditions, high-dust arrangements of SCR or SNCR-DeNOx plants need investigation of deactivation and S-conversion. NH_3 and S related fouling and corrosion downstream of the DeNOx plant may also be an issue. These issues are being investigated in Period I and continued R&D on improvements is expected. Optimal locations for de-NOx from a system point of view and technical and economically optimal de-NOx concepts for specific fuels may also include tail-end (authothermal) catalytic de-NOx concepts that should be further investigated.
- The removal of trace components in FGD and FGC for FGD and experience from air-fired wet FGD applications can be transferred to oxy-fuel conditions.
- Technologies for the removal of SO_3 and mercury for lignite-fired plants, including the applicability of SDA concepts with fabric filters.
- Waste-water treatment and minimisation

Summary table: flue gas treatment and cooling

(Colour codes: Green – validated, Yellow – partly validated, Red – not validated)

	-2020	2020-2030	2030-
SCR, SNCR, DeNOx, improvements beyond Period I (EA)			
Removal of trace components in FGD and FGC (EA)			
Technologies for removal of SO3 and mercury (EA)			
Waste water treatment and minimisation (EA)			

2.3.6 CO_2 purification and compression

For oxy-fuel, the CO_2 stream at the entrance of the compression and conditioning train can have high concentrations of components other than CO_2. R&D to develop and adapt purification technologies for such conditions is ongoing in Period I and further improvements are expected beyond this period. Improved compressor performance at such conditions, and throughout the entire load range, would contribute to reduced energy consumption. In this context, it is noteworthy that exact demands on CO_2 purity requirements imposed by transport and storage are currently unknown.

Key challenges and long-term R&D targets

- Refined handling of by-products in the oxy-fuel generated CO_2 stream remaining after the upstream cleaning steps
- Reduced compression energy consumption throughout the entire load range

R&D needs

- SOx and NOx removal in CO_2 compression train under pressurised conditions is being researched and validated in Period I and continued improvements are expected.
- Technologies for the recovery of O_2 and CO_2 from vent gas are under development and continued improvements are expected.
- Improved CO_2 compressor efficiencies at full load, as well as part load and extended load range.
- Investigations of compressor materials to verify if they can withstand the composition of the oxy-fuel generated stream
- Removal of trace components in FGD and FGC
- Technologies for the removal of SO_3 and mercury
- CO_2 dehydration: material selection, behaviour of impurities (especially NOx and SOx) in dehydration process and the treatment of regeneration gas
- Waste water treatment

Summary table: CO_2 purification and compression

(Colour codes: Green – validated, Yellow – partly validated, Red – not validated)

	-2020	2020-2030	2030-
SOx and NOx removal in CO_2 compression train under pressurised conditions, improvements after period I			
Technologies for recovery of O_2 and CO_2 from vent gas, improvements after period I			
Improved compressor efficiencies throughout load range			
Compressor design with materials that can withstand oxy-fuel generated streams			
Technologies for removal of SO3 and mercury			
CO_2 dehydration			
Waste water treatment			

2.3.7 Integrated components (including CLC)

In this section, oxygen membrane reactors and chemical looping combustion (CLC) reactors are addressed. In both cases, the separation of oxygen from air is integrated with fuel oxidation. CLC is under investigation at lab and pilot scales. There is significant cost benefit due to (nearly) complete avoidance of the air separation unit. The fuel does not meet the air directly. The oxygen needed for combustion is supplied by an oxygen carrier material which meets the fuel in the fuel reactor. This material is in a solid form and recirculated from fuel to the air reactor. The reduced oxygen carrier is oxidised in the air reactor.

Key challenges and long-term R&D targets

- Materials development (oxygen carrier material development for CLC, oxygen transport membranes)
- Reactor development with efficient fuel conversion
- Integration of the interconnected oxidising and reducing reactors to achieve reliable operation

R&D needs

- Chemical Looping Combustion:
  - Oxygen carriers (synthetically generated, naturally existing, oxygen capacity and kinetics, mechanical and chemical stability, toxicity).
  - Development of various oxygen carriers for variable fuels (coal, gas, biomass, multiple fuels)
  - Fuel conversion, including avoidance of not fully converted compounds (CO, H_2, CH_4, H_2S)
  - Validation and scale-up of oxygen carrier and ash separation
  - Reactor design, structural optimisation and scale-up
  - Use of advanced materials (e.g. ceramics, composites etc.) in reactor design
  - Scale-up
  - Integration into the power process
  - Pressurised reactors dedicated to gas-turbine operation
  - Pressurised reactors for coal, for improved kinetics
- Oxygen transport membrane (OTM) reactors: materials development, reactor development, reactor temperature control
- Integration of new oxygen separation technologies (i.e. membranes and/or adsorbent processes) with oxy-fuel boilers

Summary table: integrated components

(Colour codes: Green – validated, Yellow – partly validated, Red – not validated)

	-2020	2020-2030	2030-
CLC Oxygen carrier materials development for gas, coal, biomass or multiple fuels	Red / Yellow	Yellow	Green
O_2 carrier material stability at high T, sour and wet environment	Red / Yellow	Yellow / Green	Green
CLC Fuel conversion	Yellow	Yellow / Green	Green
CLC Oxygen carrier/ash separation	Yellow	Yellow / Green	Green
CLC Reactor design, optimisation and scale-up	Yellow	Yellow / Green	Green
CLC pressurised reactors for gas turbine operation	Red	Red / Yellow	Green
CLC pressurised reactors for coal	Red	Red / Yellow	Green
CLC reactor power process integration	Yellow / Green	Green	Green
OTM materials and reactor development	Yellow	Yellow / Green	Green
Integration of new oxygen separation technologies with oxy-fuel boilers	Red	Yellow	Yellow / Green

2.3.8 Overall process development and integration

For pilot, demonstration/full-scale testing of PF and CFB oxy-fuel power plants (10s to 100s of MW), the design of larger-size plants is based on research findings from smaller-scale plants, combined with findings from the sections listed above. As the knowledge of oxy-fuel operation increases with the number of plants, new possibilities for process integration will be easier to identify.

Key challenges and long-term R&D targets

- Scale-up and validations of oxy-fuel power plants with minimum energy penalty. This covers optimisation of heat integration and heat recovery of the entire system, including ASU and compression.

R&D needs

- Validations in pilot plants followed by demonstration plants with associated R&D programmes
- Impact of integration on system reliability and availability
- New/improved technology blocks will require subsequent validations of integration issues in pilots and demonstration plants.
- Plant integration and optimisation for efficiency and cost, including part-load performance

- Environmental integration of the power plant with respect to (e.g.) limiting the increased water usage, recovery of cooling water and low temperature heat, and waste water treatment.
- Development and implementation of dynamic models to study load change capability and control system design in the power process, as well as in specific components.

Summary table: overall process development and integration

(Colour codes: Green – validated, Yellow – partly validated, Red – not validated)

	-2020	2020-2030	2030-
Pilot and demo validation*	--	--	--
Impact of integration on reliability and availability	--	--	--
Validation and integration of improved or new technology blocks*	--	--	--
Plant integration and optimisation*	--	--	--
Environmental integration*	--	--	--
Dynamic modelling, simulations and analysis*	--	--	--

* Maturity level will depend on maturity of technology blocks

2.4 Pre-combustion technologies

2.4.1 Oxygen production for pre-combustion applications

Currently for IGCC power plants, cryogenic air separation is the only viable air separation technology due to the large scale. In the longer term, other air separation technologies based on membranes or adsorbents are seen as potential candidates.

Key challenges and long-term R&D targets

- Reduced energy consumption for oxygen production. Specific energy consumption of current cryogenic processes is dependent on oxygen pressure and nitrogen integration (use of nitrogen in the gas turbine). For oxygen at 4 MPa abs, the current range is 250-310 kWh/tonne (at ISO conditions[10]) with nitrogen integration. Without integration it is 270-330 kWh/tonne. A long-term R&D target should be to reduce this specific energy by 40 kWh/tonne for improved cryogenic processes.
- Further development of adsorbents and membranes for more energy- and cost-efficient oxygen production.

R&D needs

- Advanced cryogenic distillation, integration with other parts of the power plant or other adjacent 'cold industries' (e.g. LNG plant)
- Flexible cryogenic air separation with improved turndown and load following capabilities with minimised impact on O_2 purity and specific power consumption
- High-temperature – up to 300°C - oxygen separating membranes and adsorbents which may have the potential for efficiency improvements in IGCC (or IRCC) operation, compared to cryogenic ASU
  - Membranes for O_2 production: membrane development (flux, stability, manufacturing),
  - Membrane unit development and manufacturing for integration in the IGCC power plant
  - Adsorbent based O_2 production: adsorbent development (O_2 capacity, stability) and manufacturing methods
  - Adsorbent unit development for integration in IGCC power plant

[10] Air at 101325 Pa, 15°C, 60%RH

Summary table: oxygen production for pre-combustion applications

(Colour codes: Green – validated, Yellow – partly validated, Red – not validated)

	-2020	2020-2030	2030-
Advanced cryogenic distillation, integration with other parts of the power plant			
Flexible cryogenic air separation			
Oxygen separating membranes (flux, stability, manufacturing)			
Oxygen separating adsorbents (O_2 capacity, stability, manufacturing)			
Membrane unit manufacturing, development and process integration			
Adsorbent unit development and process integration			

2.4.2 Gasification/reforming

Through the gasification of solid fuels or reforming of natural gas, a syngas consisting to a large extent of CO and H_2 is obtained.

For solid fuels – coal, lignite as well as co-gasification with biomass – the R&D priority is to improve the availability and efficiency of the basic processes of synthesis gas production (gasification, gas treatment and conditioning, heat integration). Further objectives are to develop an optimal overall concept which does justice to the different operational requirements for commercial operation. The optimised adaption of the subsequent gas treatment to the gasification system requires additional, detailed R&D activities.

Reforming of natural gas is basically a mature technology. However, more compact and improved design with improved materials (catalysts etc.), together with material and process integration, will be possible with further developments (see section 2.4.6).

Key challenges and long-term R&D targets

- Upscaling to large gasifiers (1200-1500 MW_{th}) for single-train configuration with effective heat recovery/quench system and with low metal corrosion
- Improved gasifier slag and fly ash removal
- Increasing the efficiency in converting the chemically bound energy of the coal into that of the flue gas (cold gas efficiency)

R&D needs

- Improved coal feeding (e.g. Stamet pump for pulverised coal pressurisation)
- Improved gasifier slag and fly ash removal
- Increasing carbon conversion and the efficiency of converting the chemically bound energy of the coal into that of the fuel gas (cold gas efficiency)
- Reducing the amount of the gasification agent required (especially oxygen requirements)
- Further development of the raw gas cooling system (efficient energy use)
- Understanding material-related consequences in gasification processes
- Modelling of reactive multiphase flows for developing reaction compartments and reactor geometries
- Establishing databases as a basis for material and process modelling
- Modelling the dynamic behaviour of gasifiers for optimising process control of individual plant components

Summary table: gasification/reforming
(Colour codes: Green – validated, Yellow – partly validated, Red – not validated)

	-2020	2020-2030	2030-
Improved coal feeding			
Improved slag and fly ash removal			
Increasing the efficiency in converting the chemically bound energy of the coal into that of the flue gas (cold gas efficiency)			
Reducing the amount of the required gasification agent (especially oxygen requirements)			
Further development of the raw gas cooling system (efficient energy use)			
Understanding of material-related consequences in gasification processes (EA)			
Modelling of reactive multiphase flows for developing reaction compartments and reactor geometries (EA)			
Establishing databases as a basis for material and process modelling (EA)			
Modelling the dynamic behaviour of gasifiers for optimising process control of the individual plant components (EA)			

2.4.3 Water-gas shift

Water-gas shift (WGS) reactors are central to most pre-combustion capture power production schemes. Simplified process schemes can be developed if highly active WGS catalysts, working in the presence of significant amount of acid gases (e.g. H_2S, COS), are developed. Process schemes where CO_2 separation is carried out in the WGS reactors, either through the use of sorbents or membranes, can also be efficient alternatives to conventional schemes. These are further addressed under "Integrated components" (2.4.6).

Key challenges and long-term R&D targets
- Develop improved WGS catalysts, including sour WGS catalysts.

R&D needs
- Further development of sweet shift catalysts (improve activity and stability, reduce required steam demand)
- Development of sour shift catalysts (high activity and stability, low steam demand)
- Improved WGS reactor design (e.g. isothermal reactors)

Summary table: water-gas shift
(Colour codes: Green – validated, Yellow – partly validated, Red – not validated)

	-2020	2020-2030	2030-
Further development of shift catalysts			
Development of sour shift catalyst			
Improved WGS reactor design			

2.4.4 CO_2 capture in pre-combustion applications

In the common scheme, CO_2 is captured at high pressure in a separate step after the low temperature water-gas shift reactor. Physical solvents are the state-of-art technology for this step. Alternatives are pressure swing adsorption (PSA) processes or membranes that separate H_2 or CO_2. Process concepts based on solid sorption or membranes *integrated* into equilibrium-limited processes are addressed under "Integrated components" (2.4.6).

Key challenges and long-term R&D targets
- Reduce the energy requirement of alternative, physical solvent-based separation processes.

- Development of PSA processes based on solid adsorbents. The challenge is to find good adsorbents with high cyclic capacity in the actual pressure range. Another challenge is to find adsorbents with high selectivity for CO_2 in order to avoid the accumulation of impurities that necessitate extra thermal regeneration of the adsorbent.
- Capture of CO_2 at higher temperature to avoid the cooling down step before the combustion step
- Stability of adsorbent in the presence of contaminants such as H_2S etc.

R&D needs

- Develop solvents optimised for simultaneous separation of CO_2 and H_2S.
- Develop solid adsorbents that will adsorb CO_2 with higher selectivity than H_2S.
- Develop solid adsorbents that can separate both CO_2 and H_2S in one step.
- Low-temperature separation of CO_2 and H_2
- Hydrate-based CO_2 separation
- Membrane-based CO_2 separation
- Membrane-based H_2 separation

Summary table: CO_2 capture in pre-combustion applications
(Colour codes: Green – validated, Yellow – partly validated, Red – not validated)

	-2020	2020-2030	2030-
Optimised solvents for CO_2 and H_2S separation	Yellow	Green	Green
High cyclic capacity adsorbents with higher selectivity for CO_2 than H_2S	Yellow	Yellow / Green	Green
High capacity adsorbents for co-separation of CO_2 and H_2S	Red / Yellow	Yellow	Yellow / Green
Low-temperature separation of CO_2 and H_2	Yellow	Yellow / Green	Green
Hydrate-based CO_2 separation	Red	Yellow	Yellow
Membrane-based CO_2 separation	Red	Red / Yellow	Yellow
Membrane-based H_2 separation	Red / Yellow	Yellow	Yellow / Green

2.4.5 H_2 gas turbine

In pre-combustion capture technologies, there is a need for gas turbines that can operate on hydrogen-rich fuel gas with performance and emission levels that can match today's modern gas turbines for natural gas. Currently, gas turbines for hydrogen-rich fuels employ non-premixed burner technology using diluents such as N_2 and H_2O in order to keep flame temperature and NOx emissions down. Reduced turbine inlet temperature in order to compensate for higher moisture content and increased heat transfer is also used. These drawbacks could be overcome by some kind of dry low NOx (DLN) for hydrogen-fired gas turbines. R&D is already ongoing on DLN combustors and gas turbines for hydrogen combustion, but greater efforts are required.

Key challenges and long-term R&D targets

- Dry Low NOx burner technology without the need for large amounts of diluents
- Burner concepts for better fuel flexibility and reliability
- Increased turbine inlet temperature for higher efficiency

R&D needs

- Improved or new burner concepts based on a low-emission mode of operation
- Validated numerical design tools, including detailed resolution of fuel/air mixing and combustion, and high-quality laboratory facilities with advanced measurement technologies, to enable reliable validation
- New GT cooling technologies, high temperature materials and hot path coatings
- Component testing and demonstration under relevant conditions
- Testing a large gas turbine within the scope of a demonstration plant

Summary table: H_2 gas turbine
(Colour codes: Green – validated, Yellow – partly validated, Red – not validated)

	-2020	2020-2030	2030-
Improved or new burner concepts	Yellow	Green	Green
Validated numerical design tools (EA)	Yellow	Green	Green
New cooling technologies and high temperature materials	Yellow	Green	Green
Component testing at relevant conditions (EA)	Yellow	Green	Green

2.4.6 Integrated components

Major simplifications of process schemes may be obtained by the integration of components and/or material development. Typically, by combining a sorbent or membrane and an equilibrium-limited reaction, the equilibrium of the process can be shifted drastically, making subsequent separation and/or purification steps redundant.

Key challenges and long-term R&D targets

- Reducing the size of equipment and increasing the conversion by combining reaction and separation in single units
- Making use of more advanced materials (membranes, sorbents, high temperature CO_2 and O_2 solid carriers) that will be a more integrated part of the process
- Material manufacturing methods and costs
- Cyclic capacity, stability and compatibility of sorbent in reaction conditions
- Flux and stability of membrane in reaction conditions
- Long-term stability and performance of materials in a harsh environment

R&D needs

- Sorption-enhanced reforming/gasification (SER): SER is based on the capture of CO_2 in a gasification (reforming) reactor using sorbent particles or CO_2 carriers to react with CO_2-forming carbonate. Due to the capture of CO_2, the equilibrium is shifted towards H_2. As a result, gasification (reforming) and the shift reaction are undertaken in a single process step, typically at temperatures of 500°C to 700°C and at elevated pressure. The produced carbonate has to be calcined (regenerated) in a separate step. The most commonly used process design is an interconnected fluid bed reactor system. There are several experimental results with biomass published from laboratory-scale prototypes (10-100s of kW) operating in continuous mode. Novel schemes have recently been proposed combining endothermic CO_2 carrier regeneration with exothermic stages in CLC cycles, allowing for more efficient processes operating with large fixed beds at high temperatures and pressures. These are mainly designed for natural gas reforming. The application to solid fuels raises concerns regarding the conversion rate, in-situ sulphur capture, sorbent/carrier/catalyst durability etc.
- Sorption-enhanced water-gas shift: in this high pressure process, a sorbent is used to remove CO_2 from gas streams during the water-gas shift reaction, shifting the equilibrium towards improved H_2 yield and negligible rests of CO and CO_2 in the effluent. The sorbent has to be regenerated in a separate step in a cyclic manner. As a result of the high pressure, PSA processes are most commonly envisaged, but TSA processes can also be considered. Major challenges are to find sorbents with high cyclic capacity and stability under the reaction conditions used (typically 200°C to 450°C, 20-40 bar, high steam pressure) and to handle any H_2S present. High consumption of steam to regenerate the material is one of the challenges.
- Chemical Looping Reforming (CLR) employs an oxygen carrier for the reforming of natural gas to produce a syngas for a natural gas-based, pre-combustion decarbonisation process. The process is similar to CLC (described in section 2.3.7), but sub-stoichiometric.

- Membrane water-gas shift reactors: in a similar manner as for sorbent-enhanced water-gas shift, a hydrogen or CO_2 permeable membrane is used in-situ to remove product gases during reaction, thus shifting the equilibrium towards higher conversions. The most challenging issue is to develop membranes with high flux, selectivity and stability at the relevant reaction conditions – temperatures from 200°C to 450°C and elevated pressure. For Pd alloy membranes, the main challenge is high stability and scaling up the manufacturing of the membranes and modules while reducing the cost.
- Hydrogen membrane reformers: in a similar manner as for sorbent-enhanced reforming, a hydrogen permeable membrane is used in-situ to remove hydrogen during reaction, thus shifting the equilibrium towards higher natural gas conversions. The most challenging issue is to develop membranes with high flux and stability at the relevant reaction conditions – temperatures from 500°C to 800°C and elevated pressure. The focus should be on scaling up the manufacturing of membranes and modules.
- Oxygen transport membrane reactors: OTM may find applications in large-scale processes for oxygen production (air separation unit), for chemical production (syngas produced from autothermal reforming, ATR or partial oxidation, POX) and for energy conversion (coal to liquid, coal to gas, oxycombustion and IGCC processes). These processes require a very large quantity of O_2 at high temperature (above 500°C) and pressure. The main challenges are to improve membrane integration by increasing the surface/volume ratio to increase the membrane lifetime and to scale up the manufacturing of membranes and modules while reducing costs.

Summary table: integrated components

(Colour codes: Green – validated, Yellow – partly validated, Red – not validated)

	-2020	2020-2030	2030-
Sorption enhanced water-gas-shift	Red / Yellow	Yellow	Green
Sorption enhanced reforming/gasification	Red / Yellow	Yellow	Green / Green
Chemical looping reforming	Red / Yellow	Yellow	Green
Membrane water-gas-shift reactors	Red	Yellow	Yellow
Hydrogen membrane reformers	Red	Red / Yellow	Yellow
Oxygen transport membrane reactors	Red	Red / Yellow	Yellow

2.4.7 Overall process development and integration

If the classical individual components and the overall IGCC concept are further optimised, then electrical efficiencies above 50% without CO_2 separation seem to be possible. A precondition for this improvement is a gasifier adapted to the IGCC concept and the development of gas-cleaning processes that run at elevated temperatures and also, if possible, operate in a dry mode. Further potential for process optimisation lies in the integration of an air separation unit, CO conversion and CO_2 separation within the IGCC process.

In particular, when targeting the integration of novel technologies (see section 2.4.6) with the aim of improving the process performance, new challenges are likely to appear in overall process development. As the knowledge of IGCC operation increases with the increasing number of plants, new possibilities for process integration will be easier to identify.

IRCC plants (pre-combustion capture based on the reforming of natural gas) currently appear to have a high power penalty, but their attractiveness may increase with the development of novel, integrated components (see section 2.4.6). Hence there may also be a need for overall process development and integration for this type of power cycle with CO_2 capture.

Key challenges and long-term R&D targets

- Low availability
- Long start-up time
- Poor part load efficiency of IGCC
- Finding the best integration of novel (integrated) components for performance improvement

R&D needs

- Optimised power plant concepts with reduced auxiliary power consumption
- Overall process integration and optimisation, including start-up and part-load aspects
- New/improved technology blocks will require subsequent validations of integration issues.
- Environmental integration of the power plant with respect to (e.g.) cooling water requirements, liquid effluents and their purifications
- Development and implementation of dynamic models to study transients in the power process, as well as in specific components

Summary table: overall process development and integration
(Colour codes: Green – validated, Yellow – partly validated, Red – not validated)

	-2020	2020-2030	2030-
Power plant concepts with reduced auxiliary power consumption*	--	--	--
Integration and optimisation including start-up and part-load*	--	--	--
Validation of integration of new/improved technology blocks*	--	--	--
Environmental integration*	--	--	--
Dynamic modelling, simulations and analysis*	--	--	--

* Maturity level will depend on maturity of technology blocks

2.5 Technologies and research areas for improved CO_2 capture performance

This section lists R&D topics connected to the technology blocks in Table 1 that are not marked in bold, plus other areas related to the performance improvement of power plants with CO_2 capture beyond 2020.

2.5.1 Advanced steam cycle technology

CCS technologies have a negative impact on the net efficiency of modern pulverised coal-fired power plants. An intelligent and cost-effective use of CCS technologies therefore requires new strategies to increase the net efficiency of these plants. The most promising include:

- Increase working steam temperature and pressure in new Ultra Super Critical (USC) power plants (up to and maybe beyond 350/370 bar, 700/750°C) and hence increase the severity of fireside operating conditions, as well as potential new internal oxidation damages and higher creep.
- Promote long-term efficiency increase in existing and next-generation USC power plants, reducing/ eliminating out-of-service accidents and introduce maintenance criteria based on provisional material-component evolution models.

Key challenges and long-term R&D targets
All the technologies mentioned above are scientifically viable, but bring severe technological challenges in terms of materials/components reliability, especially increased resistance of metallic components to creep and creep fatigue in complex thermo-mechanical conditions (e.g. non-steady state working conditions).

- Increased resistance of ceramic components (e.g. refractory) to thermal shock and fatigue
- Increased resistance of ceramic and metallic materials to oxidation/hot corrosion, erosion-abrasion and wear under increased operating pressure
- Increased knowledge of microstructure instability during service, as expected in high alloyed metallic materials and ceramic components operating under highly demanding environmental conditions (e.g. atmosphere composition, temperature, pressure, multi-axial strain-stress)

- Improved component design criteria, taking account of material response in service (e.g. thermal cycling stresses, high thermal expansion in austenitic steels and nickel-base alloys, differential behaviour at welds and joints)
- Improved inspection procedures and maintenance strategies through a strong integration of field data from advanced sensor/monitoring systems and output from metallurgical physical-chemical and thermo mechanical models, in order to describe component behaviour during service and provide tools to assist plant operating decisions

R&D needs

- Innovative solutions in material science (e.g. Fe-base and Ni-base materials, ceramics, coatings)
- Improvement in manufacturing techniques (melting, large forging/casting, rolling/extruding, welding etc.)
- Improvements in design criteria of materials and components for application in very demanding environments (e.g. high temperature, hard fume composition, variable multi-axial load) through the integration and development of engineering + metallurgy evolution models and new experimental test procedures and configurations (e.g. creep-fatigue tests on pipes, including welds)
- Improvement in material performance databases through advanced experimental tests at medium- and full-scale test loop(s)/rig(s)
- HT sensoring for improved Process Control
- Definition and promotion of new/improved EN, ISO and National Standards for the application of new engineering solutions, as well as improved, non-destructive testing methods.

Summary table: USC technology (700-750°C).

(Colour codes: Green – validated, Yellow – partly validated, Red – not validated)

	-2020	2020-2030	2030-
Innovative materials solutions			
Manufacturing techniques improvements (EA)			
Design criteria for materials and components in demanding environments (EA)			
Materials performance database improvements (EA)			
HT sensoring for improved process control			
New/improved EN, ISO, National Standards as well as better non destructive testing methods (EA)			

2.5.2 Other technology development

Ensuring cost-effective CO_2 capture processes requires improved knowledge and standards for processes, components and interdisciplinary areas not directly linked to the technology blocks in Table 1.

R&D needs

- Improved fuel handing, in particular fuel feed to pressurised systems, e.g. gasifiers.
- For fuels with high moisture contents (e.g. lignite), atmospheric and pressurised fluidised bed fuel-drying technologies are being developed and expected to be demonstrated in Period I. Further improved and optimised fuel-drying technologies that could be integrated efficiently into power plants could contribute to higher efficiencies.
- Improved CO_2 compressors (robust, high efficiency, part-load capability)
- H_2S removal at high temperatures. Gasification of coal yields a sour syngas. Innovative technologies such as membranes and sorbents will require or benefit from sulphur removal at higher temperatures,

usually prior to the water-gas shift process. Adsorption at high temperatures and membranes are possible candidates for sulphur removal.

- Multi-component removal processes. Simultaneous removal of H_2S/CO_2/-Hg/dioxin etc.
- Improved knowledge of CO_2 properties
- Improved knowledge of heat transfer characteristics for high CO_2 content mixtures
- Design tool improvements: current process design tools are typically based on either chemical engineering or mechanical engineering principles and an interdisciplinary approach is needed.
- Improved heat exchangers
- Oxy-fuel piston engines for power generation
- Evaluation of novel power cycle concepts based on working fluids other than water/steam (e.g. supercritical CO_2 and organic fluids) and how CO_2 capture could be heat integrated with these concepts

Summary table: technology development
(Colour codes: Green – validated, Yellow – partly validated, Red – not validated)

	-2020	2020-2030	2030-
Improved fuel handing (EA)	Yellow	Green	Green
Improved and optimised fuel-drying technologies	Yellow	Green	Green
Improved CO_2 compressors	Yellow	Green	Green
H_2S/sour gas removal at high temperatures	Yellow	Green	Green
Multi component removal processes.	Yellow	Yellow / Green	Green
Improved knowledge of CO_2 properties (EA)	Yellow	Green	Green
Improved knowledge of heat transfer characteristics for high CO_2 content mixtures	Yellow	Green	Green
Design tool improvements (EA)	Yellow	Green	Green
Improved heat exchangers	Yellow	Green	Green
Oxy-fuel piston engines for power generation.	Red	Yellow	Green
Processes with other working fluids than water/steam and their heat integration with CO_2 capture*	---	---	---

*Maturity will depend on the considered process

2.5.3 System studies

In addition to process and component related R&D needs described above, there is also a lack of knowledge within overall system related topics.

R&D needs

- Investigation of total environmental footprint from different types of power generation with CO_2 capture
- Research on the operation of fleets of power plants with CO_2 capture (connected to more than one infrastructure, electric power grid, CO_2 network and possibly also H_2 network). Today, power plant operation is optimised with respect to daily power demand variations and what prices can be achieved. CO_2 capture has to become a parameter in this so that the capture is optimised and balanced between short-term power demand variations and yearly CO_2 quota. This kind of system analysis could be based partly on research on CO_2 value chains.
- Research on how to integrate CCS and fuel cells in energy systems: fuel cells represent the most energy efficient power production and the combination of fuel cells and CCS is an option worth investigating for reducing CO_2 emissions. R&D are needed to optimise the integration of fuel cells and CCS.

- Studies on large- vs. small-scale CCS applications: from a long-term perspective, small-scale CCS could be commercially viable. Small-scale power production with small-scale CCS could be a possibility for green power production for all small villages in developing countries that do not have electricity today. Studies are needed to compare the technological and economic aspects of small- and large-scale CCS. Key challenges to be addressed are small-scale transport and storage of CO_2.
- A research framework that enables tight integration between technology development on different scales and research areas, e.g. solvent-capture process-power process and membrane-membrane reactor-power process. The purpose of such R&D should be to obtain good design targets for solvents or materials and the best possible integration in a dedicated power process.

2.6 CO_2 capture from power plants

This section provides general recommendations on how to continue research on CO_2 capture from power plants, as well as recommendations specific to each capture route.

For the latter, a qualitative analysis was made of how the R&D topics described for the three different capture routes in sections 2.2-2.4 would affect the decision-making parameters in Table 2. For each R&D topic, it was assessed whether a success in research would result in a significantly positive or negative impact on any of the seven decision-making parameters, or have no significant impact. The qualitative results obtained were then analysed together with the information in the summary tables in sections 2.2-2.4. The results are presented below following the general recommendations.

2.6.1 General recommendations

Overall energy system studies are needed of power plants with CO_2 capture operating as an integral part of energy systems with a high share of renewables. This means studying the interactions with solar and wind power – which must be combined with power plants with a high capability to follow load demands in the power grid – as well as CO_2 capture from biofuels (Bio-CCS). Such studies should also cover CO_2 transport and storage, and recognise the importance of power plant availability and operability. Depending on whether power plants with CCS are intended for base-load operation or as load followers, there will be differences in process design which need further attention. The future development of the electric power market will determine whether there will be any need for base-load power plants.

There is a general recommendation to undertake research on novel – potentially ground-breaking – technologies which could radically improve the performance of CCS, if such technologies emerge. Overall power process development and investigations into the integration of novel CO_2 capture related technologies into power processes and other industrial processes will continue to be important as capture technologies evolve.

Highly efficient retrofittable CO_2 capture solutions should be supported in order to address the urgent issue of locked-in carbon, i.e. CO_2 emissions from newly-built fossil fuel power plants without CO_2 capture.

Ultra Super Critical (USC) steam technology development is highly important for increasing the efficiency of coal-based post-combustion and oxy-fuel technologies. Likewise, the development of advanced gas turbines for achieving higher turbine temperatures is important for natural gas-fired plants and IGCC.

Pilot-scale testing is key to advancing technologies such as novel solvents, sorbents, membranes and CLC on the road to large-scale demonstration. A prerequisite for pilot testing of any technology is that promising performance has been verified both experimentally at lab scale and in studies of full-scale power plant performance. As a follow-up to successful pilot scale testing, an estimation of the potential when scaling up to demonstration- and/or full scale is required.

Finally, it should be noted that the weighting factors assigned to the investment decision-making parameters in Table 2 also provide guidance for R&D on CO_2 capture-related technologies. In particular, it may be observed that there is little knowledge on the availability and operability of many technologies. As they become more mature and show promising performance both technically and economically, it is therefore important to undertake such analyses.

2.6.2 Post-combustion capture technologies

There is an overall recommendation to undertake research on post-combustion capture technologies for coal and other solid fuels, as well as natural gas. Both types of fuels must be able to respond to load changes in the power system due to a high share of renewables such as solar and wind power. Natural gas- fired power must be able to respond more rapidly to load change requirements than coal.

R&D on CO_2 enrichment in flue gas through recycling part of the gas turbine exhaust (often referred to as exhaust gas recirculation, EGR) should be undertaken in order to increase the efficiency of post-combustion capture from natural gas. Impact on CAPEX and OPEX is estimated to be positive, although a negative impact on power plant operability from the gas turbine is possible. That said, the natural gas combined cycle already has a very good operability, so some reduction should be acceptable in this case.

Post-combustion capture power plants are a commercially available technology. It is a fact that commercial amine-based liquid solvents are on the market and that large-scale CO_2 capture units are being built for commercial power plants. However, there is a potential for improvement, requiring further R&D on next-generation technologies, as described below.

R&D on improved liquid solvents based on current commercial technologies, but with reduced energy penalty, should continue. R&D on novel liquid solvents, with a potential to significantly reduce the energy penalty should also be pursued. Examples include (but are not limited to) dual phase liquids, ionic liquids, precipitating solvents, as well as enzymes for catalysing CO_2 absorption/desorption. Energy and cost-efficient capture processes that utilise improved and novel solvents must also be developed.

R&D on solid sorbents should continue since there could be a positive effect on process efficiency compared to (current) liquid solvents and there could also be a positive impact on HSE. The operability and availability of power plants using solid sorbents for CO_2 capture, compared to liquid solvents, should be assessed. There are possible synergies between calcium looping (which is the most mature example of solid sorbent technology) and CO_2 capture in the cement industry that calls for further research.

HSE is the main concern for current solvents and successful R&D on improved/novel solvents, sorbents or membranes is expected to improve the HSE of post-combustion capture, compared to current technology.

There is little support within ZEP to continue research on hydrates as a post-combustion capture technology (particularly due to the estimated low maturity), or pursue anti-sublimation (i.e. freeze-out of CO_2[11]). However, there may be industrial applications for the latter. Recommendations for further R&D in these areas, when related to power plants, should be well-founded to be pursued and there may be advantages that have been omitted by ZEP.

This report does not include any integrated components for post-combustion technologies (section 4.1). However, hybrid technologies, or combinations of technologies, may have been omitted that will prove to have a positive impact on one or several of the investment decision-making parameters, e.g. a combination of first applying CO_2 membranes for CO_2 enrichment of the flue gas, followed by liquefaction of CO_2 to separate it from other exhaust gas components; and possibly other innovative concepts that are either entirely new or combine known technologies in novel ways.

[11] Not to be confounded with low-temperature capture in the pre-combustion capture route which is based on CO_2 liquefaction technology

2.6.3 Oxy-fuel technologies

The overall recommendation is to pursue R&D for oxy-fuel combustion: much has been undertaken on oxy-fuel for coal to prove that the technology is feasible and can become competitive, but efforts are still needed to make the technology marketable and economical – in particular, system-wide optimisation. However, it should be noted that large demonstrations (100s of MW_{th}) of the entire oxy-fuel and capture route for coal have been planned, including completed FEED studies, and the technology is estimated to become commercially viable as a result. This should be supported by continued validations and R&D as there is also the potential for improvements, as described below.

Advanced (more efficient) and flexible cryogenic air separating unit R&D should be pursued in order to improve oxy-fuel power plant efficiency and operability. Oxygen-separating membranes and solid sorbents are generally expected to have a positive impact on process efficiency, but a negative impact on operability and possibly also availability of the oxy-fuel plant. Time to commercialisation is estimated to be longer for membranes than adsorbents, but the overall estimate is that when realised, membranes will prove to be the preferred alternative to sorbents for efficient oxygen separation in the longer term. The development of most improved oxygen separation methods, including the advanced cryogenic ASU, is estimated to have a small negative impact on power plant CAPEX, which should be balanced by the estimated positive impact on efficiency.

Pursuing the oxy-fuel capture route also means that R&D on oxy-fuel boilers and the overall oxy-fuel process should be continued. There are several opportunities for efficiency increase through boiler R&D, although some high-potential R&D topics (e.g. increased O_2 concentration, pressurised oxy-fuel boilers and oxy-fuel boilers capable of switching to air-firing mode) could have a negative impact on availability and operability, requiring dedicated R&D. CO_2 purification and compression is an important issue for oxy-fuel + coal and some R&D topics (e.g. improved CO_2 compressor efficiency) are also relevant for oxy-fuel + natural gas. Oxygen transport membrane reactors[12] for integration in oxy-fuel boilers are estimated to have a definitive positive impact on process efficiency, but OPEX and CAPEX, as well as operability and availability, are estimated to be worse than for oxy-fuel boilers with conventional cryogenic ASU.

In the case of oxy-fuel combustion for gas turbine-based processes (natural gas-based power production), more R&D is needed before it can be determined whether this CO_2 capture route is competitive when evaluated against the investment decision parameters in Table 2. At the current state of knowledge, no definitive conclusions can be drawn; it can only be observed that the technology has no obvious showstoppers, but there may be operability challenges that require dedicated R&D.

Chemical Looping Combustion (CLC) is a technology that, in the long term, can offer power processes with the potential for high efficiency and potentially also high CO_2 capture rate. For CLC, improved fuel conversion, new oxygen carrier materials, reactor design and power process integration are important R&D topics. Little research has been done on the operability and availability of CLC processes, but should be undertaken in order to evaluate whether they are acceptable in this respect. Pressurised reactors for coal and gas CLC could have significant efficiency advantages, but also face significant challenges and should be regarded as high risk/high gain R&D areas.

2.6.4 Pre-combustion technologies

The overall recommendation is that research related to the Integrated Gasification Combined Cycle (IGCC) should be pursued. IGCC, when implemented with modern technology, has the potential to produce power from coal at a higher efficiency than the conventional pulverised fuel combustion of coal, plus the ability to convert solid fuels of varying quality (including biomass) into electricity.

[12] Oxygen membranes and oxygen membrane reactors are two slightly different types of technology. In the oxygen membrane reactor, an oxidation or combustion reactor takes place in the same compartment as the oxygen separation from air.

It should be noted that IGCC technology with CO_2 capture is commercially available with both state-of-the-art ASU and existing gas turbines (which show a slight reduction in efficiency since they are manufactured for operation with natural gas). The main R&D needs for improving IGCC performance relate to improved ASU, improved gas turbine efficiency with high H_2-content in the fuel gas and improvements in the syngas cleaning section (at high temperature). This will improve the efficiency of the IGCC plant beyond 2020 and therefore also reduce CO_2 capture costs.

As for oxy-fuel, advanced (more efficient) and flexible cryogenic ASU R&D should be pursued in order to improve power plant efficiency and operability. However, the integration and optimisation of air separation technologies is different for IGCC than for oxy-fuel. Oxygen-separating membranes and solid sorbents are generally estimated to have a positive impact on process efficiency, but a negative impact on operability and possibly also availability of the IGCC. Time to commercialisation is estimated to be longer for membranes than for adsorbents, but the overall estimate is that when realised, membranes will prove to be the preferred alternative to sorbents for efficient oxygen separation in the longer term. The development of most improved oxygen separation methods, including advanced cryogenic ASU, is estimated to have a small negative impact on power plant CAPEX, which should be balanced by a positive impact on efficiency.

Improvements in gasifiers for IGCC should also be pursued, e.g. improved slag and fly ash removal, improved fuel conversion, reduction in the amount of gasification agent required and improved coal feeding.

For H_2 gas turbines, the recommendation is straightforward: as long as R&D is pursued on the IGCC capture route, R&D must also be pursued on efficient, low-emission hydrogen gas turbines. Once this has been realised, improvements will always be necessary to keep track of those in conventional gas turbines.

Positive results are expected from further R&D on water-gas shift (WGS) reactors – in particular, the further development of shift catalysts (including sour shift catalysts) and improvements in WGS reactor design. As it concerns the separation of CO_2 and H_2 in the shifted syngas, it is noted that current commercial solvents for CO_2 separation at conditions typical for IGCC have a rather low energy penalty. Nevertheless, R&D on alternative separation technologies (e.g. H_2-separating membranes, sorbents and low-temperature separation of CO_2, with a focus on availability and operability) should be supported for implementation in the longer term to enable further efficiency improvements.

Integrated components for pre-combustion capture (see section 2.4.6) are generally estimated to have a positive impact on process efficiency and possibly also on CAPEX (due to a reduction in the number of process components), but with an estimated negative impact on availability and operability. It should be emphasised that more research could still be done to assess the impact of integrated components on all investment decision-making parameters.

Technology development related to pre-combustion capture from power plants contains elements (in particular, separation technologies and integrated components) which may prove very useful for H_2 production with CO_2 capture in industrial applications. It is therefore recommended not to focus research on the Integrated Reforming Combined Cycle (IRCC) due to its anticipated poor operability (in particular load-following capacity) compared to a NGCC with post-combustion capture. Natural gas-based pre-combustion technologies should potentially focus on H_2 production with CO_2 capture.

Annex: Bio-CCS and CCS in industries beyond power

This report covers R&D needs for CO_2 capture in the power sector, primarily based on fossil fuels. However, the EU Energy Roadmap 2050 confirms that CCS combined with biomass can deliver "carbon negative" values, while the IEA underlines that CCS in energy-intensive industries must deliver half of the global emissions reductions required by 2050 from CCS.[13] In general, all the CO_2 capture technologies described in this report can have applications beyond fossil fuel-based power.

Bio-CCS: the only large-scale technology that can *remove* CO_2 from the atmosphere

In 2011, the European Biofuels Technology Platform (EBTP) and ZEP set up a joint taskforce (JTF) Bio-CCS to review the various technology routes for combining CCS with biomass conversion. This resulted in a landmark report[14] that covers CCS with the production of biofuels, electricity/heat from biomass (both co-firing and 100% biomass combustion), as well as Bio-CCS options for energy-intensive industries.

The report shows how several biofuel production routes offer a near-pure stream of CO_2 as an integral part of their processes, opening the way for very low-cost CCS deployment where economies of scale can be applied, or where adjacent CO_2 transport and storage infrastructure can be shared. Co-firing biomass with coal or lignite at moderate percentages (at least up to 10%) is also not expected to increase the costs of CCS deployment. (N.B. This refers to the cost of co-firing, not the cost of biomass relative to fossil fuels as this varies highly.) However, for higher co-firing rates and dedicated biomass combustion, higher investment costs and efficiency penalties may be expected.

The composition of biomass fuels is variable, but they generally have a higher alkaline content than fossil fuels which can, for example, lead to ash deposition and corrosion when co-firing with fossil fuels in boilers. The report of the JTF Bio-CCS states that mode data and research is needed on these issues, as well as other potential technological challenges.

Most of the CO_2 capture R&D topics described in this report should be investigated from a biomass point of view and all three capture routes could, in principle, be adapted to biomass power production. Some emerging capture systems (in particular, those operating at high temperatures 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. This includes both co-firing and 100% biomass applications in order to identify the most feasible technology options. Indeed, if optimised and cost-effective biomass production is achieved, some variants could be ready before 2030, at the latest (i.e. in Period II, as defined in section 2.1.1). 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.

Realising the significant potential for CCS in industries *beyond* power

According to the IEA, CCS represents the most important new technology option for reducing direct emissions in industry. Indeed, in some industries, such as steel and cement, it is the *only* means of achieving deep emission cuts, with the potential to mitigate 2-2.5 gigatonnes of CO_2 per year globally by 2050.[15] In Europe, several industries are already currently implementing CCS at pilot scale.

In 2012, ZEP therefore created Working Group (WG) Other Industries in order to review technology synergies and options for CCS deployment in energy-industries and seek cooperation with representatives

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[13] IEA: www.iea.org/publications/freepublications/publication/name,38764,en.html

[14] "Biomass with CO_2 Capture and Storage (Bio-CCS) – The way forward for Europe": www.zeroemissionsplatform.eu/library/publication/206-biomass-with-co2-capture-and-storage-bio-ccs- the-way-forward-for-europe.html

[15] IEA Energy Technology Perspectives, 2012

of those sectors. In 2013, ZEP published its report, "*CO_2 Capture and Storage (CCS) in energy-intensive industries: an indispensable route to an EU low-carbon economy*".[16]

Table 3 shows the various energy-intensive industries, the chemical processes involved, relevant separation technologies and their stage of development and deployment. Further modifications could be required to several of the technologies since they are generally optimised for CO_2 capture from power plants, e.g. there may be differences in impurities in the CO_2 captured, or in CO_2 partial pressure.

Apart from technology synergies, cooperating with these industries could enable clustering of activities to achieve economies of scale for CO_2 transport *and* storage infrastructure, plus other synergies such as the (re)use of excess heat. In some cases, joint capture units may even be applicable. It is therefore essential that this is taken into consideration when planning new units.

Table 3: Summary of capture technologies for energy-intensive industries and their maturity in relevant sectors

Separation technology	Industry	Process	Process redesign	Stage of development and deployment	Relative cost per t CO_2 at time of deployment	Capture rate	Reference	Comment
Chemical or physical absorption (2.2.1/2.4.4)	Fertiliser	Ammonia synthesis (Haber-Bosch)	No	Commercial	Low	>95%	(De Coninck & Mikunda, 2011) (Zakkour & Cook, 2010)	Stream purity depends on design of the process, but can be almost pure. N.B. This is the capture rate of the CO_2 not used in production of urea
	Natural gas extraction	Natural gas upgrading	No	Commercial	Low	>95%	(Zakkour & Cook, 2010)	
	Synthetic fuels	Fischer-Tropsch, methanol-to-gasoline	No	Commercial	Low	50%	(Carbo, 2011)	Not listed explicitly, but assumed to be chemical absorption. Only 5% is lost as flue gas; the remainder is captured in Fischer-Tropsch liquids and char.
		Hydrogen	No	Commercial	Low	>90%	(Carbo, 2011)	
	Ethylene oxide	Direct ethylene oxidation	No	Pilot	Low	>95%	(Zakkour & Cook, 2010)	The process of reactor gas stream clean-up includes removal of the CO_2 using physical sorbents, Hot Potassium Carbonate process (e.g. the Benfield process), or cryogenic separation techniques to give a high purity stream.

[16] www.zeroemissionsplatform.eu/library/publication/222-ccsotherind.html

	Iron and steel	Direct Reduced Iron (DRI)	No	Pilot	High		(ETSAP, 2010)	
	Cement	Kiln/ Calcination	No	Pilot	High	77 -85%	(De Coninck & Mikunda, 2011) (UNIDO, 2010)	UNIDO assumption for monoethanolamine (MEA) post-combustion absorption
	Refineries	Hydrogen (natural gas reforming or partial oxidation)	No	Commercial	Low	>95%	(UNIDO, 2010)	
		Hydrogen	No	Commercial	Low	>95%	(UNIDO, 2010)	Feed stream often close to 100% CO_2
		Fluidised Catalytic Cracking (FCC)	No	Pilot	Medium		(UNIDO, 2010)	
		Boilers and process heaters	No	Research	High	>95%	(UNIDO, 2010)	
	Aluminium	Electrolysis of aluminium oxide from bauxite	No	Research	High			Cost reduction possible if aluminium plant exhaust can be fed to a gas turbine combined cycle for CO_2 enrichment before capture.
	Offshore	Stand-alone power production from gas turbines	No	Research	High	>95%	(Winden, et al., 2011)	
Membrane separation (2.2.1)	Natural gas extraction	Natural gas upgrading	No	Commercial	Medium	>95%	Zakkour and Cook (2010)	
	Synthetic fuels	Fischer-Tropsch, Methanol-to-Gasoline	No	Research	Medium	>90%	(Richard C. Baliban, 2012)	
		Hydrogen	No	Research	Medium	>90%	(L. Barelli, 2008)	
Pressure swing adsorption (2.2.1/2.4.4)	Synthetic fuels	Hydrogen	No	Research	Medium	80-90%	(Carbo, 2011)	Not used in isolation; also used with other absorption techniques
	Iron and Steel	Direct Reduced Iron (DRI)	Yes	Research	Medium		(ETSAP, 2010)	
		HIsarna	Yes	Research	Medium	70%	(De Coninck & Mikunda, 2011)	

	Refineries	Hydrogen (natural gas reforming or partial oxidation)	No	Research	Low	>90%	(Y Ding, 2000)	
Oxy-fuel (2.3)	Iron and Steel	Oxy-fuel blast furnace	Yes	Pilot	Medium	85-95%	(De Coninck & Mikunda, 2011)	
	Cement	Kiln/Calcination	Yes	Research	Medium	52%	UNIDO (2010)	Assumes partial capture oxy-fuel technology
	Refineries	Fluidised Catalytic Cracking	Yes	Pilot	Medium		(Mark Crombie, 2011)	
		Boilers and process heaters	Yes	Research	Medium	>90%	(Morten Seljeskog, 2005)	
Calcium looping (2.2.1)	Cement	Kiln/Calcination	Yes	Research	Low	>90%	(C.C. Dean, 2011)	Integration synergies possible with CO_2 capture from other large point source (i.e. Coal power plant)
Chemical looping combustion (2.3.7)	Refineries	Boilers and process heaters	Yes	Research	Low	>90%	(María Ortiz, 2012)	Integration synergies possible with cement manufacture
Chemical looping reforming (2.4.7)	Synthetic fuels	Hydrogen	Yes	Research	Low	>95%	(Magnus Rydén, 2006)	
	Refineries	Hydrogen	Yes	Research	Low	>95%	(Magnus Rydén, 2006)	Feed stream is often close to 100% CO_2

Eligible capture source at site: the share of on-site emissions which can be feasibly captured is difficult to quantify even at a high level, owing to plant-specific considerations and limitations in the knowledge available on CCS for industrial applications. The maximum available share may range from 75-80% for iron/steel works and oil refineries, and up to 100% for CHP units.

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