Technology Innovation Needs Assessment (TINA)

Carbon Capture & Storage in the Power Sector
Summary report

August 2012

Background to Technology Innovation Needs Assessments

The TINAs are a collaborative effort of the Low Carbon Innovation Co-ordination Group (LCICG), which is the coordination vehicle for the UK's major public sector backed funding and delivery bodies in the area of 'low carbon innovation'. Its core members are the Department of Energy and Climate Change (DECC), the Department of Business, Innovation and Skills (BIS), the Engineering and Physical Sciences Research Council (EPSRC), the Energy Technologies Institute (ETI), the Technology Strategy Board (TSB), the Scottish Government, Scottish Enterprise, and the Carbon Trust. The LCICG also has a number of associate members, including the Governments of Wales and Northern Ireland, Ofgem, the Crown Estate, UKTI, the Department for Transport, the Department for Communities and Local Government, the Ministry of Defence, and the Department for Environment, Food and Rural Affairs.

The TINAs aim to identify and value the key innovation needs of specific low carbon technology families to inform the prioritisation of public sector investment in low carbon innovation. Beyond innovation there are other barriers and opportunities in planning, the supply chain, related infrastructure and finance. These are not explicitly considered in the TINA's conclusion since they are the focus of other Government initiatives, in particular those from the Office of Carbon Capture and Storage in DECC and from BIS.)

This document summarises the Carbon Capture and Storage TINA analysis and draws on a much more detailed TINA analysis pack which will be published separately.

The TINAs apply a consistent methodology across a diverse range of technologies, and a comparison of relative values across the different TINAs is as important as the examination of absolute values within each TINA.

The TINA analytical framework was developed and implemented by the Carbon Trust with contributions from all core LCICG members as well as input from numerous other expert individuals and organisations. Expert input, technical analysis, and modelling support for this TINA were provided by Ecofys Consultancy.

Key Findings

CCS has tremendous potential to help the UK and the world effectively meet GHG and energy security targets. Innovation across the CCS technology chain could reduce UK energy system costs by £10-45bn[1] to 2050, and innovation to ensure the security of long-run CO_2 storage remains particularly critical to CCS viability. Innovation can also help create a UK industry with the potential to contribute further economic value of £3-16bn to 2050. Significant private sector investment in innovation, catalysed by public sector support where there are market failures, can deliver the bulk of these benefits with strong value for money.

Potential role in the UK's energy system	• CCS offers many benefits to a low-carbon energy and economic system: (i) it allows the flexibility and energy security benefits of fossil fuel combustion with near-zero GHG emissions; (ii) when applied to biomass firing, it serves as a source of relatively low-cost negative emissions; (iii) it is applicable to industrial power and process emissions, which are particularly costly to reduce. • Energy system modelling suggests that electricity generation with CCS could deliver c.10-35% of total generation by 2050, with c.11-60GW in capacity. This depends primarily on public acceptance of alternatives (wind and nuclear), the availability of biomass, and the overall energy demand. The application of CCS to industry offers further deployment potential, but is not assessed in this report. • Having CCS available (compared to an energy system without CCS) is estimated to save the UK hundreds of billions of GBP in cumulative value between 2010 and 2050. Nevertheless, considerable work remains to demonstrate CCS at large scale and across the entire chain (capture-transport-sequester-secure), and widespread deployment is unlikely prior to 2020.
Cutting costs by innovating	• The key technological components of carbon capture, transport and injection have been demonstrated at commercial scale, however, component costs and efficiency penalties remain high and uncertain, and many challenges related to full integration remain to be tackled. • Full-scale, source-to-sink demonstration is particularly urgent to prove scalability of CCS, and its long-run availability to the system. Moreover, it is necessary to drive cost-reduction opportunities related to full plant integration, and to identify the most important component technology innovations. • Critically, the assurance of very long-term CO_2 storage with a very high degree of certainty is still unproven. This constitutes a significant risk to the viability of CCS and its rapid roll-out in the near to mid term. • Innovation has the potential to drive down the costs (ignoring fuel) of conversion with capture by 15% by 2025 and 40% by 2050. Innovation can further reduce the long-run costs of transport by ~50% and of storage by >50%. Innovation in measuring, monitoring & verification (MMV) and mitigation & remediation (M&R) can ensure the security of sequestered CO2, reducing the financing costs of CCS, as well as enabling its overall availability as an abatement option. • Successful innovation could reduce the costs to the UK of CCS deployment by £10–45bn to 2050. • On top of this, >>£100bn in systems savings would result from CCS availability (by reducing the need for more expensive alternatives).
Green growth opportunity	• UK suppliers could play a significant role in the global CCS market, with a 4-6% share of a market with potential cumulative gross value-added of between £150 - 750bn up to 2050. • If the UK successfully competes in a global market to achieve the market share above, then the CCS related industry could contribute £3 – 16bn to UK GDP up to 2050 (with displacement effect).
The case for UK public sector intervention	• Public sector activity is required to unlock this opportunity – although in some areas the UK may be able to rely on other countries to drive this innovation. – Market failures include uncertain demand (externality effect), infrastructure needs (public good effect), difficult to insure liabilities, and uncertain environmental impacts and regulatory regime. – In many core areas the UK *could* rely on other countries, although there is a strong case for UK support in areas of niche UK strength or distinct UK need (e.g. deep sub-sea storage and MMV)
Potential priorities to deliver the greatest benefit to the UK	• Innovation areas with the biggest benefit to the UK are (i) deep sea storage, MMV and M&R; and (ii) advanced capture development (especially gas and biomass) and demonstration of integrated conversion-capture. In both, the UK should look to lead or join multi-national partnerships • Given specific niche strengths, there is also a case for broad "open call" support for leading ideas with "breakthrough" potential (e.g. novel capture or compression concepts, etc.) • Supporting all of the UK's priority innovation areas would require hundreds of millions of GBP over the next 5-10 years (leveraging 2-3 times that in private sector funding). The UK is addressing some of these innovation areas, but there remains considerable scope to expand this activity.

[1] Cumulative (2010-2050) present discounted values in low-high scenarios for the savings driven by 'learning by research' (see below)

Chart 1. CCS TINA summary

Sub-area	Focus	Value in meeting emissions targets at low cost £bn[2]	Value in business creation £bn[3]	Key needs for public sector innovation activity/investment
Capture and pollution control components	Gas and biomass firing/co-firing	4 (2 – 7)	1.5 (0.5 – 3)	• Development & demonstration of biomass related capture technologies to accelerate promising technologies to commercial readiness • Development & demonstration of retrofit capture technologies gas and/or biomass, and potentially for coal in areas where strong UK-based technology advantage exists • R&D of novel capture concepts with breakthrough potential
Conversion and generation	Boilers, turbines and gasification element	4 (2 – 8)	3 (1 – 6)	• Development & demonstration in the boiler/turbine/GTCC area of gas fired oxyfuel concepts (e.g. medium scale CHPs) • Development & demonstration of multifuel (coal, waste, biomass) gasification in combination with multifuel output (syngas, hydrogen, power and CO_2), in combination with integrated capture concepts
Plant operation		4 (2 – 8)	2 (0.3 – 4)	• Development & demonstration of services for optimised operation of power plants with capture (screening study potentially needed to identify clear priorities)
CO_2 Transport	Optimised design	2 (0-5)	1 (0.3 – 2)	• Design of optimised transport network, including onshore and offshore transport options, and cost/risk mitigation parameters
CO_2 Storage	Deep sub-sea injectivity, infrastructure and key components	4 (2 – 8)	1 (0.3 – 2)	• Development of tools for geological characterisation, performance simulation, and risk assessment (environmental impact assessment, etc.) • Development & demonstration of cost-reducing components and procedures for deep sub-sea injection and storage infrastructure (re-use and new build)
MMV and M&R	Deep sub-sea and transport network	4 (2 – 8)	0.5 (0.2 – 1)	• Development & demonstration of low-cost, high reliability, continuous monitoring options (e.g. remote or well bore sensing) for storage (especially deep sub-sea) • Development & demonstration of low-cost, very high reliability, continuous monitoring options for MMV near to compression point, and along transport network • Development & demonstration of measurement tools for CO_2 flow and quality • R&D of novel risk mitigation and remediation technologies for deep sub-sea storage, followed by early demonstration for promising concepts
Full integration	***Across components***	***>100***	***Enabler of all value identified***	• ***Full-scale, source-to-sink demonstration of integrated CCS plant to prove concept at scale, and reduce costs through system level integration improvements***
Total	**Component level** **Full integration**	**£22bn (10 – 45)** **>£100bn**	**£8bn (3 – 16)**	**5-10 year investment in the hundreds of millions of GBP (programmes of material impact in individual areas in the millions to tens of millions of pounds)** **5-10 year investment in the low billions of GBP across multiple demos (one full scale demo approximately £1bn)**

Benefit of UK public sector activity/investment[4]	
	High
	Medium
	Low

[2] 2010-2050 Medium deployment / High improvement (L/H – H/H)
[3] 2010-2050 with displacement
[4] Also taking into account the extent of market failure and opportunity to rely on another country but without considering costs of the innovation support

CCS could play a critical role in the UK energy system

Although necessarily more expensive than unabated fossil fuel energy generation, CCS is expected to be a relatively low cost method of reducing GHG emissions (comparable to wind and nuclear), especially when considering full energy system requirements. CCS offers many unique benefits to a low-carbon energy and economic system:

- CCS allows the flexibility and energy security benefits of fossil fuel combustion to be maintained while reducing the emission of greenhouse gases (GHGs), and their contribution to climate change
- When applied to biomass firing, CCS can reduce emissions even further, potentially as a source of relatively low-cost negative emissions
- CCS could be applied to industrial power generation and process emissions, which are particularly hard and expensive to reduce
- As the technology develops, CCS could potentially be applied to the atmosphere itself

Having CCS available (compared to an energy system without CCS) is estimated to save the UK hundreds of billions of GBP in cumulative value between 2010 and 2050. Nevertheless, CCS as an integrated system and many of its key components remain at a relatively early stage of development and demonstration from a UK perspective:

- There is no full-scale demonstration of a CCS technology chain directly replicable in the UK (Norway and North America have commercial scale CCS, but with major dissimilarities to CCS technology chains expected in the UK)
- Smaller-scale standalone versions of technologies that will potentially be involved in UK CCS chains have been demonstrated in various industries, but their cost remains well above the general target range of £10-15/tonne CO_2
- Techniques to assure the long-term security of sequestered CO_2 have yet to provide the degree of certainty required for either insurability or robust regulatory standards

The improvement potential from innovation is very large (detailed below), and will be critical to ensuring *both* that costs are in line with expectations *and* that the full CCS chain will be deployable at mass scale by ~2020. Various energy system modelling exercises suggest that CCS could effectively deliver c.10-35% of total generation by 2050.

While innovation will play an important role in ensuring CCS is deployed cost effectively and in a timely manner, the overall capacity installed depends even more significantly on key "exogenous" factors, especially the degree of public acceptability of onshore wind and nuclear, the availability of biomass for energy use, the overall energy/electricity demand, and the relative success of energy efficiency and demand reduction measures.[5]

We have highlighted a range of potential deployment levels for CCS assuming successful innovation. These indicative scenarios depend on what one believes about the exogenous factors affecting the future energy system[6]:

- **Low scenario** (1.5GW by 2020, 11GW by 2050) if there are few constraints on nuclear and onshore wind, energy demand is relatively low (through successful energy efficiency and demand reduction measures), low amounts of biomass are available for energy needs
- **Medium scenario** (1.5GW by 2020, 30GW by 2050) if there are moderate constraints on nuclear and/or onshore wind (e.g. nuclear and onshore wind <50-60GW), energy demand is moderate (owing to only partial success of reduction measures), and biomass is available in line with consensus expectations
- **High scenario** (5GW by 2020, 60GW by 2050) if there are strong constraints on nuclear and onshore wind (e.g. nuclear and onshore wind <20GW), biomass availability is limited, OR energy/electricity demand is relatively high

These deployment scenarios were generated based on CCC MARKAL runs for the fourth carbon budgets, DECC 2050 calculator scenarios, and customised runs of the ESME model for this work. This determines how much capacity is required across the generation mix to meet energy demand and emissions reduction targets at lowest cost based on the constraints outlined above. The medium scenario is used as the central scenario for all of the TINA analyses below.

This TINA only considers the innovation needs associated with CCS from power generation. Industrial CCS is also likely to be necessary, with innovation needs differing from those of the power sector, related to emissions captured from industrial processes or heat production. Modelling suggests that industrial CCS could be comparable in size to CCS for the power sector in terms of millions of tonnes of CO_2 captured through to 2050. Scenarios show industrial CCS capturing anywhere from 15% to 100% the amount of CO_2 captured by the power sector (with central estimates at about 33%). An assessment of the innovation needs and opportunities in industrial CCS is recommended for future work.

[5] Deployment levels of CCS also depend on adherence to current emissions reduction targets, and on the development of a robust regulatory regime around MMV, environmental impact, and health and safety. Our analysis assumes these elements are adequately addressed.

[6] These scenarios aim to capture the full range of feasible deployment scenarios, and are neither forecasts for the UK nor targets for policy makers. By trying to capture the full range of uncertainty over the mid to long term to inform innovation policy, these indicative deployment levels were not precisely aligned with UK government short and mid-term targets.

Cutting costs through innovation

Current costs

We assume initial costs of conversion with CCS (n^{th} of a kind) of between £1.1m and £3.6m per MWe, with CCGT+CCS at the low end, and Biomass IGCC at the high end[7]. These costs remain very uncertain owing to CCS's relatively early stage of development and demonstration. Moreover, the relative capital and operating costs cannot be taken to indicate the relative attractiveness of different conversion and CCS options, since (i) levelised costs are highly uncertain, owing to dependency on input costs which themselves are hard to predict; and (ii) the levelised cost of energy does not factor in potential differences in GHG emissions from different plants which is a key factor in the *social* attractiveness of a given technology. As such, we conduct the analysis assuming an illustrative suite of options for CCS deployment, including Combined Cycle Gas Turbine (CCGT), Advanced Supercritical Coal, (Biomass) Integrated Gasification Combined Cycle (IGCC), Circulation Fluidized Bed (for biomass), Oxyfuel Combustion, and the potential integration of Solid Oxide Fuel Cells (SOFCs) with either CCGT or IGCC. This is supported by system modelling, which shows the deployment of specific plant types to be quite sensitive to relatively small changes in cost assumptions.

To gauge innovation potential, CCS technology chains were broken down into major innovation sub-areas (as detailed in Chart 2), where various components were common across different CCS deployment options.

Chart 2. Overview of CCS sub-areas by share of cost

Sub-area[1]	Descriptions	Share of cost of energy c. up to 2050[1]
CO_2 Capture and pollution control components	▪ Pre, post and oxyfuel capture concepts (including air separation and CO_2 compression) ▪ Air pollution controls (including selective catalytic reduction, flue gas desulphurization and electrostatic precipitator)	16%
Conversion and generation components	▪ Combustion boiler and turbine (for coal and/or biomass feedstocks) ▪ Gasifier area, gas turbine combined cycle, and all related component elements (Heat recovery steam generator/ steam turbine/ Gas turbine)	33%
CO_2 Transport (pipe system)	▪ Design and planning approval for transport network ▪ Physical infrastructure consisting of a mix of trunklines (e.g. max. capacity of 60 Mt/yr), satellite pipelines, and "source-to-sink" pipelines (e.g. max. capacity of 5 Mt/yr)	4%
CO_2 Storage	▪ Well design, materials, drilling, injection & completion for a mix of approaches including platforms and deep sub-sea structures, as well as new and re-used wells ▪ *NB: Significant CO_2 reuse opportunities not considered in detail (see below)*	4%
MMV and M&R (including pre-injection storage modelling)	▪ Storage characterisation, performance simulation and risk assessment ▪ Suite of measuring, monitoring & verification technologies (e.g. remote and atmospheric sensing, near surface and deep subsurface monitoring, and intelligent MMV networks) ▪ Mitigation & remediation (M&R) – various potential technologies	2%
Fuel costs	▪ The costs of coal, gas and biomass according to an indicative mix of future fuel requirements ▪ *Can be reduced by improvements in overall plant efficiency (driven by the core conversion and capture components, and their effective integration and operation)*	41%

[7] CCS costs depend critically on factors such as the level of competition in the supply chain, efficient financing mechanisms, world commodity prices, and the value of the Pound. In the case of CCS, which is not yet deployed significantly at commercial scale, costs remain highly uncertain. This analysis attempts to factor out this uncertainty, and focus on the impact of innovation (all else equal). As such, the anchor costs assumed do not necessarily represent the actual costs, but rather a reasonable base cost from which to assess the potential for innovation improvements.

Cost and efficiency improvements through innovation

CCS as an integrated system, and many of its key components remain at a relatively early stage of development and demonstration with significant additional improvement potential. There is no full-scale demonstration of a source-to-sink CCS technology chain that is directly applicable to the UK power sector – Norway and North America have commercial scale CCS, but with significant dissimilarities to CCS technology chains required for at-scale, long-term application to the power sector. Smaller-scale standalone versions of technologies that will potentially be involved in UK CCS chains have been demonstrated and/or are commercially deployed in various industries, but their cost remains well above the general target range of £10-15/tonne CO_2. Finally, techniques to assure the long-term security of stored CO_2 have yet to provide the degree of certainty required for either insurability or robust regulatory standards.

Chart 3. Identified cost savings from innovation by component

	Component area	Innovation impact by c.2025	Innovation impact by 2050	Key sources of improvement potential – high level summary
CO_2 Capture and pollution control components	Pollution controls	2%	7%	▪ Improve energy efficiency, and cleaning effectiveness for future needs (i.e., biomass, oxyfuel, IGCC+SOFC)
	Capture components (including compression)	20%	50%	▪ Improve solvents, adsorbents, membranes for CO_2 removal ▪ Adapt to biomass needs (e.g. impurities, dilute CO_2, etc.) ▪ Optimise WGS and develop SEWGS (pre-CC) ▪ New compression (e.g. RAMGEN) and ASU concepts
Conversion and generation components	Boiler/turbine	11%	22%	▪ Improve efficiency (advanced materials, higher steam parameters); Improve design and handle issues (e.g. fouling) related to oxyfuel
	Gasifier area	33%	60%	▪ Increase operating pressure, improve fuel feeding, integration of oxygen/hydrogen storage; advanced concepts (e.g. chemical looping); adaptation to biomass feedstocks
	GTCC	15%	35%	▪ Improve efficiency (e.g. through increased inlet temperature), and adapt for optimal firing of H_2 rich fuels
Overall plant efficiency	*Improvement in efficiency rates*	16%	28%	▪ *Component improvements (as above)* ▪ Process integration (flue gas, waste treatment, pre-treatment of fuel, etc.) - e.g. recycle part of the flue gas to the compressor to enhance CO_2 concentration and use waste heat
CO_2 Transport (pipe system)	Optimal "back-bone" design	c.50%		▪ Design "back-bone" network to optimise network size/location ▪ Design to manage the integration of intermittent supplies of CO_2 into a storage system that desires constant CO_2 delivery
CO_2 Storage	Infrastructure choice	c.50%		▪ Improve infrastructure planning, assessment, mothballing and hibernation techniques to maximize pre-use and minimise cost
	Injectivity effectiveness	100% improvement in injectivity rates		▪ Improve well design, drilling and completion (e.g. horizontal drilling) ▪ Improve well materials – e.g. casing, linings and cements resistant to CO_2 and other co-contaminants ▪ Injection equipment that can handle variable CO_2 flows
	Component costs	c.25%		
MMV and M&R	Component costs	35%		▪ Better understanding of geological/geochemical impacts (e.g. chemical reactions, effects of pressure, fluid flow, brine management, etc.) ▪ Integrate various performance simulation approaches and use better fundamental geochemical understanding to improve models ▪ Intelligent monitoring networks, and advanced sensing technologies, including remote, atmospheric, near surface & deep sub-surface ▪ Optimise protocol for remediation measures, and develop advanced mitigation techniques (e.g. micro-drilling, sealants, chemical additives)
	Risk minimisation	4-6% reduction in levelised costs		
Total		15-20%	c.40%	

Innovation opportunities were assessed through a review of existing studies, and were based on learning rates for conversion and capture components, and on absolute improvement estimates for transport and storage. Over the next 10-15 years cost improvement potential for the CCS technology chain as a whole is estimated at c.15-20%, with further improvement to 2050 estimated to bring down costs by c.40%, all vis-à-vis "initial n^{th} of a kind" costs holding fuel costs constant. The source of improvement by "component" is shown in Chart 3.

This study does not look at *CO_2 reuse* options in detail. Overall, only a handful of reuse options were considered to have potentially material impact (i.e. >20MtCO_2 reused per year): Enhanced Oil Recovery, Enhanced Coal Bed Methane Recovery (ECBM), Enhanced Gas Recovery (EGR), urea yield boosting, micro-algae cultivation, calcium/magnesium carbonate, CO_2 concrete curing, and liquid fuels (renewable methanol, formic acid, etc.). Of these, many are already commercially available, and were not considered to have large innovation potential. Technologies with significant improvement potential for the UK have been addressed at a high level, either here or in other TINA analyses:

- ECBM and EGR: Considered here, especially as concerns general aspects of geological storage, MMV and M&R
- Calcium/magnesium carbonate and CO_2 concrete curing: Considered in separate TINA analysis of cement sector
- Micro-algae: Considered in separate TINA analysis of bio-fuels and bio-feedstocks

Value in meeting emissions and energy security targets at lowest cost

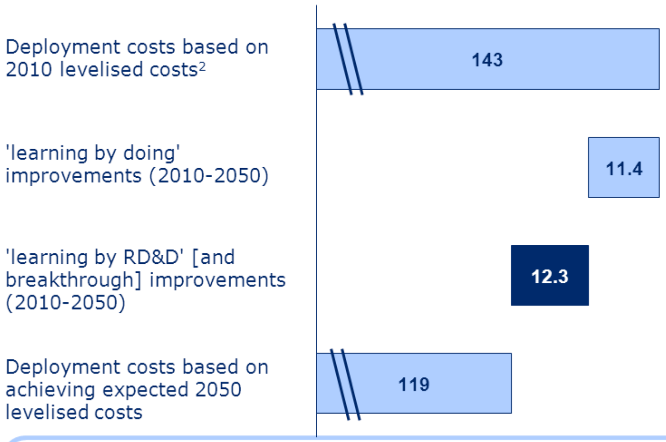
Based on our cost and efficiency improvements, and our scenarios for deployment (taking into account emissions and energy security constraints), we calculate a total potential savings in energy system costs through innovation of £41bn. This represents the maximum innovation potential, combining 'learning by research' (driven by RD&D spending) and 'learning by doing' (achieved through the incremental learning associate with increased deployment alone). In our calculations, we separate out 'learning by doing' from 'learning by research' (based on the stage of each components development and historical experience) to give a more specific estimate of the impact potential for RD&D programmes.

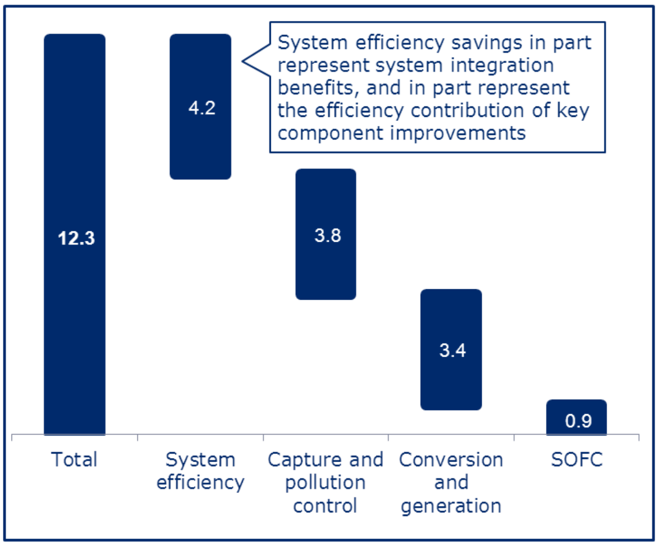
In the conversion and capture components, and overall generation plant integration the identified innovation opportunities lead to a saving of £24bn in deployment costs over 2010-2050 (medium scenario). As shown in the left hand side of Chart 4 below, over half of this is from improvements driven by 'learning by research'. The right hand side of Chart 4 illustrates the key component areas driving this savings potential. This allocation is not meant to be a precise breakdown, but gives a rough sense of relative potential impact. Significantly, there is a large chunk of improvement driven by overall system efficiency, which will likely result from both specific component improvements as well as the effective integration of those components across the plant.

In the areas of transport, storage, MMV and M&R, the identified innovation opportunities lead to a saving of £17bn in deployment costs over 2010-2050 (medium scenario). As shown in the left hand side of Chart 5 below, £10bn of this is from improvements driven by 'learning by research'. The right hand side of Chart 5 illustrates the key component areas driving this savings potential. This gives a rough sense of the relative potential impact across the areas, with the biggest potential in various aspects of storage, MMV and M&R.

Chart 4. Value of innovation in meeting emissions and energy security targets at lowest costs (2010-2050) – Conversion and capture components

Resource cost savings estimate based on conversion and capture innovation[1]
Cumulative 2010-2050, discounted £bn, medium deployment/high innovation scenario (based on Global IEA Blue map)





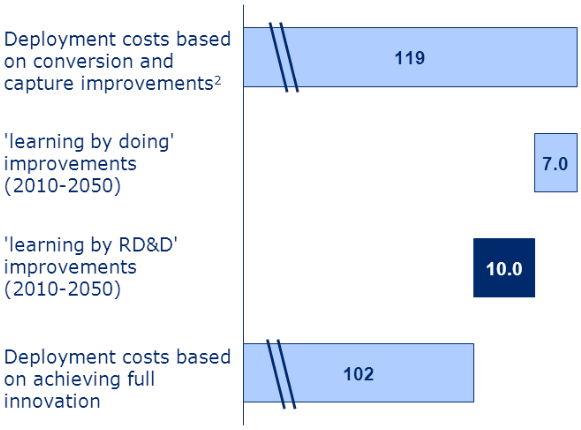
Sensitivity
- High deployment scenario (high learning) results in £279bn deployment cost with overall £46bn of cost reduction due to innovation.
- Low deployment scenario (low learning) results in £69bn deployment cost with overall £11bn of cost reduction due to innovation.

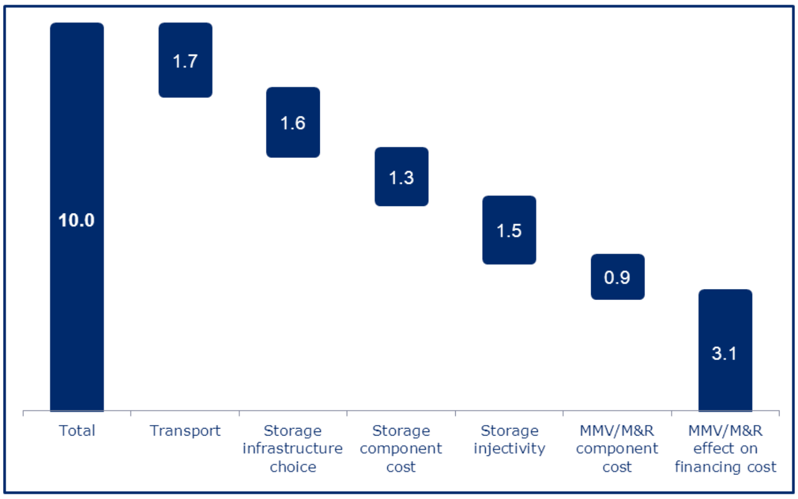
Learning by doing vs. Learning by research
- Bottom up assessment of each component's stage of development was used to determine the proportion of innovation likely to come from learning by doing vs. learning by research – see appendix for more details
- Roughly 1/3 of the savings from innovation (~£8.4bn) comes through overall system efficiency improvements. We assume these improvements are split 50-50 between learning by doing vs. research

[1] The underlying counterfactual is that costs and efficiency do not improve without innovation. Although in other TINAs (see offshore wind), we use two counterfactual estimation methodologies. Since CCS deployment levels are relatively insensitive to cost improvements, the savings estimates do not vary significantly depending on our counterfactual methodology in this case (see full TINA analysis).
[2] Cumulative levelised cost of capacity installed between 2010 and 2050 discounted to 2010 using the social discount rate

Chart 5. Value of innovation in meeting emissions and energy security targets at lowest costs (2010-2050) – Transport, storage, MMV and M&R components

Resource cost savings estimate from transport and storage innovation[1]
2010-2050, discounted £bn, medium deployment/high innovation, Global IEA Blue map





Learning by doing vs. Learning by research
- Since transport infrastructure design is not a serial process benefitting from repeated deployment of similar components, we assumed "learning by research" is the dominant source of transport cost improvements
- In storage, MMV and M&R, we assume that innovations represent a mix of emerging and mature technologies, and we split the effects of learning by doing vs. learning by research as we did with capture and conversion

Sensitivity
- High deployment scenario results in "learning by research" savings of £20.8bn (£4.8bn for Transport, £8.3bn for Storage, and £7.7bn for MMV/M&R)
- Low deployment scenario results in "learning by research" savings of £3.8bn (*none* for Transport, £1.9bn for Storage, and £1.9bn for MMV/M&R)

[1] The underlying counterfactual is that costs and efficiency do not improve without innovation. Although in other TINAs (see offshore wind), we use two counterfactual estimation methodologies. Since CCS deployment levels are relatively insensitive to cost improvements, the savings estimates do not vary significantly depending on our counterfactual methodology in this case (see full TINA analysis).
[2] Cumulative levelised cost of capacity installed between 2010 and 2050 discounted to 2010 using the social discount rate

Full-scale plant and source-to-sink integration, as well as "lynch-pin" innovations in storage, MMV and M&R are critical to unlocking deployment

In addition to the value of sub-system or component innovation (both learning by doing and research) in reducing the cost of deploying CCS versus current expected costs (i.e. by £22.3bn and £18.4bn respectively in our medium scenario), it is important to highlight the additional value to the energy system of simply having CCS available. Energy system modelling and various sensitive runs show that CCS deployment is very insensitive to cost assumptions and that CCS will be an attractive option even at current expected costs estimates. This is due its relative cost advantage, its flexibility/dispatchability and its potential negative emissions benefits. All of this makes it a particularly attractive option in a 'low-carbon' energy system.

When testing the impact on energy system costs of having CCS available (at current technology costs) *and* of reducing levelised costs of energy through sub-system/component innovation, we found the former's impact was almost an order of magnitude greater than the latter's (see Chart 6 below).

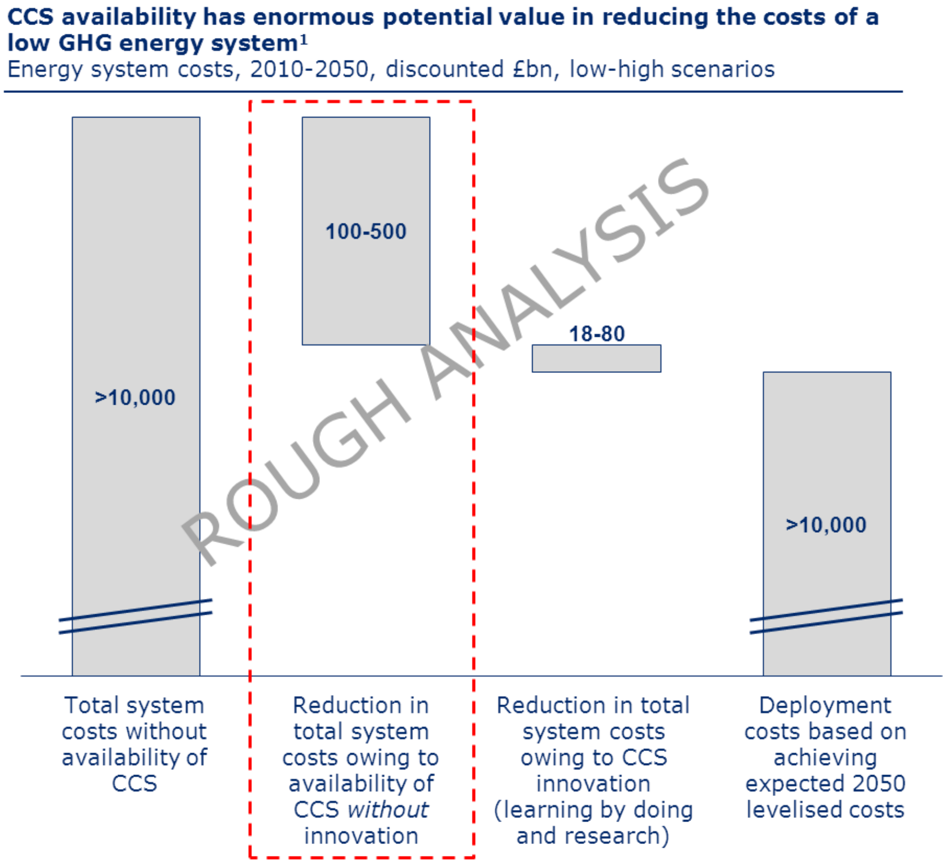
This provides strong support for the need to:

1. demonstrate and prove the scalability of CCS from source-to-sink with a fully-integrated plant at commercial-scale;
2. ensure that any critical technological obstacles to deployment are addressed robustly (we define the technologies addressing these critical obstacles as "lynch-pin" technologies).

Currently, the only area considered technically unproven involves the assurance of very long-term CO_2 storage with a very high degree of certainty. While some specific technology advances in conversion, capture and CO_2 injection technologies remain unproven, there are currently available technologies which can perform all of these functions. In contrast, a definite portfolio of technologies that can assure the security of very long-term CO_2 storage cannot be said to have been proven. Hence we have defined three technology areas as "lynch pin":

- Storage characterisation, simulation and risk assessment
- Measuring, monitoring and verification
- Mitigation and remediation

Chart 6. While innovation could reduce the cost of deploying CCS by tens of billions of GBP, ensuring CCS is available could reduce the energy system costs of meeting targets by hundreds of billions of GBP



[1] Based on comparing total energy system costs in ESME-TINA modelling runs with and without CCS. Runs were conducted with varying fuel prices, including a high scenario (based on DECC fossil fuel forecasts) with coal at £90/tonne, and gas at $18/mmbtu in 2050.

Green Growth Opportunity

A large global carbon capture, transport and storage market

A large amount of CCS is expected to be required globally as well as in the UK, with International Energy Agency (IEA) estimates as high as 1,000GW or more by 2050. We look at three indicative scenarios:

- **Low scenario** (22GW by 2020, 202GW by 2050) – there are large demand reductions and high nuclear deployment, and global emissions well above 14Gt or significant technical, economic or policy issues with CCS cause limited CCS penetration. Based on IEA Baseline, with some CCS take up from pilot plants (~20% capacity of IEA BLUE Map)
- **Medium scenario** (62GW by 2020, 431GW by 2050) – global emissions fall to 14Gt by 2050, there are large demand reductions, there is high deployment of renewables with some constraints on nuclear, and the deployment of CCS is delayed or capture efficiencies are relatively low. Based on IEA BLUE Map – High Renewables
- **High scenario** (109GW by 2020, 1011GW by 2050) – global emissions fall to 14Gt by 2050, there are some constraints on nuclear, and there is successful demonstration and timely scale up of coal and gas CCS (also Bio-CCS installed). Based on IEA BLUE Map

Based on these scenarios and the expected cost of CCS technologies over time, we estimate that the global market turnover by 2050 could grow to £25bn – £130bn (£45bn in medium scenario) (real, undiscounted value). In the medium scenario, this represents potential cumulative, discounted gross value added (GVA)[8] between 2010 and 2050 of £396bn. Since GVA is better than market turnover as an indicator of the actual contribution of business activity to the economy, we use it to drive our analysis and conclusions below. See Chart 7.

[8] Although the CCS sector is not sufficiently developed to know the precise ratio of GVA to turnover, we estimate the likely GVA-turnover ratio for each major CCS sub-system by using the current GVA-turnover ratio in similar industries

Chart 7. Estimated market turnover and GVA by CCS sub-area

Sub-area[1]	**Global market turnover,** cumulative 2010-2050, £bn undiscounted			**Global market turnover,** cumulative 2010-2050, £bn discounted			**GVA/ turnover**	**Global market value,** cumulative 2010-2050, £bn discounted			**Global market value** 2020, £bn undiscounted High scenario	**Global market value** 2050, £bn undiscounted High scenario	**Comments global undiscounted market value** £bn undiscounted High scenario
	Low	Medium	High	Low	Medium	High		Low	Medium	High			
Pollution control components	24	**47**	118	11	**26**	56	c.63%	7	**16**	35	1.8	4.2	Max 4.3 Yr 2045
Capture components	58	**136**	289	29	**76**	145	c.63%	18	**48**	91	5.2	9.2	Max 9.9 Yr 2040
Conversion and generation	191	**418**	955	88	**218**	441	c.57%	50	**123**	250	12.7	34.9	Max 37.0 Yr 2040
Operation of plants with carbon capture	116	**299**	578	48	**131**	239	c.65%	31	**85**	156	6.3	30.8	Max 30.8 Yr 2050
Transport	71	**190**	355	28	**79**	142	c.63%	18	**50**	90	3.2	21.3	Max 21.3 Yr 2050
Storage	59	**158**	296	24	**66**	118	c.63%	15	**41**	75	2.7	17.8	Max 17.8 Yr 2050
MMV and M&R	41	**111**	207	17	**46**	83	c.70%	12	**32**	58	1.9	12.4	Max 12.4 Yr 2050
TOTAL	**560**	**1,358**	**2,798**	**245**	**642**	**1,225**		**151**	**396**	**754**	**33.8**	**130.5**	

The UK could be a strong player in a number of market areas

The UK has the capabilities to become a strong player in various CCS markets. Nevertheless, the global scale of the market and the high degree of international competition, mean that likely market shares are estimated to be in the range of 3-6%. Key elements of potential competitive advantage include the following:

- **Conversion and generation components:** The UK is home to a number of leading players with global operations, although at least 4-5 other countries can lay claim to equal or greater strengths. The competitive advantage in boilers is estimated to be greater than in steam turbines and IGCC components (although some work exists in the latter areas as well). UK based companies also have the *potential* to develop a competitive CO_2 compression concept, although this is not an area of current strength.
- **Capture components:** The UK is home to a number of leading players with global operations, although again, at least 4-5 other countries can lay claim to equal or greater strengths. The UK has competitive advantage in certain areas of post-combustion, Oxyfuel and pre-combustion capture.
- **Transport, storage, MMV and M&R components:** The UK is unlikely to be a leader in onshore transport and storage, however, the UK has world class capability in the areas of offshore engineering which are applicable to transport and storage. MMV and M&R (especially offshore) lag behind in their market development and there are not yet clear market leaders. The UK has some distinct RD&D capabilities, and could potentially be among the leaders in these fields. Finally, the UK has large offshore storage capacity which could serve a number of northern European countries.
- Across all areas of the CCS value chain, **engineering and contracting services** are considered a UK strength

Depending on this relative competitive advantage, market shares are expected to vary by component area, from ~3% in post-combustion capture and gasification (competing against established foreign competitors) to ~6% in storage capital infrastructure (leveraging the UK's offshore engineering capabilities and storage availability).

£3 – 16bn net contribution to the UK economy

If the UK successfully competes in a global market (e.g. exporting technology components, professional services, or CO_2 storage) to achieve the market share above, then the CCS-related sector could contribute c.£1bn (£0.3 – 2bn)[9] in GVA per annum by 2050, a cumulative contribution[10] of c.£22bn (£6 – 43bn)[9] to 2050.

It may be appropriate to apply an additional displacement effect since part of the value created in the export market will be due to a shift of resources and thus cancelled out by loss of value in other sectors. Expert opinion has roughly assessed this effect to be between 25% and 75%. Including a 50% displacement factor, CCS would make a net annual GVA contribution of c.£0.5bn (£0.1 – 1bn)[9] by 2050, and a cumulative net contribution of c.£8bn (£3 – 16bn)[9] to 2050.

See Chart 9 below.

The case for public sector activity

Public sector activity is required to unlock this opportunity – both the £22bn reduction in the cost to the energy system from learning by research, and the c.£8bn net contribution to UK GDP from new business creation.

Market failures impeding innovation

A number of overall market failures inhibit innovation in CCS, with impacts across the full chain of technologies:

- **Policy dependent demand and uncertain support levels –** CCS by its nature requires a clear carbon price/penalty to be economically viable, hence the value of the component technologies depend fundamentally on a credible policy regime. Even more than renewables, the nature of the incentives for CCS is likely to be complicated and full of additional risks, including accounting of and liability for fugitive emissions
- **Barriers to developing novel/innovative concepts** – very high uncertainty, long lead times, and spillover risks mean that individual companies lack confidence in their ability to generate or capture returns on investment
- **Key infrastructure dependency on uncertain public investment –** Uncertainty regarding infrastructure availability and cost discourages both project and technology developers, and inhibits innovation. Key uncertainties include unclear willingness of governments to underwrite critical infrastructure such as pipelines, unclear rules regarding storage site approval, etc.
- **Long-term, global liabilities difficult to insure against –** Climate liability is effectively global, and issues need to be overcome through the accounting rules specified in international climate legislative frameworks. The relatively long time frame of carbon storage, and reluctance of private entities to participate in CCS projects if they risk being liable ‘forever’
- **Uncertain environmental impacts and regulatory regime –** Various negative environmental consequences of equipping plants with CCS could undermine public acceptance and cause difficult approval process. Issues include high water consumption, increase in waste streams, increases in NOx emissions, etc.

Within the value chain, specific market failures are further detailed in Chart 8 below.

[9] Medium (Low – High) deployment scenarios

[10] Discounted at 3.5% to 2040, and 3.0% between 2040 and 2050, in line with HM Treasury guidelines

Chart 8. Market failures in CCS innovation support

Sub-area	What market failures exist?	Extent
Capture components (pre, post, oxyfuel, etc.)	1. **Policy dependent demand and uncertain support levels** inhibit innovation in capture at all stages, and create a ***need for support from development through full demonstration*** – Inherent cost and energy penalty mean no market exists without support, and long lead times and long-run nature of plant investments mean that support must be stable in the long-run – Certain components (e.g. air separation unit and CO_2 compression) do have other applications that drive innovation, but probably not the significant breakthroughs needed for CCS applications 2. **Barriers to developing novel/innovative concepts** (very high uncertainty, long lead times, and spillover risks that inhibit individual companies from make required investments) – This creates a ***need for support to earlier stage, breakthrough technologies***	*Critical failures*
Air pollution controls (SCR, ESP, FGD, etc.)*	▪ Market for air pollution controls (flue gas equipment, sulphur removal, etc.) exists in absence of CCS, hence innovation less dependent on to policy demand support ▪ However, advanced requirements related to CCS integration suffer from failures (1) and (2) above, potentially creating a ***need for support to specific breakthrough technologies***. Key areas include highly efficient flue gas cleaning systems for post-combustion, air pollution control for oxyfuel concepts, and technologies related to the efficiency of IGCC concepts (e.g. hot gas clean up)	*Some significant failures in specific applications*
Conversion and generation	▪ *Boilers and turbines are* mature components for conventional power plant market, hence less affected by support uncertainty and barriers to novel concepts. While advances in materials and higher steam parameters needed to increase steam cycle efficiency (and reduce energy penalty of CCS), commercial returns will likely drive improvements. Nevertheless, some advanced requirements related to CCS integration suffer **from failures (1) and (2)** above, creating a ***need for support to modification and demonstration***. Key areas include boilers/turbines specifically designed for oxyfuel concept, and improvements related to firing/co-firing of biomass ▪ **Barriers to novel concepts** exist for the IGCC application of gas turbines for hydrogen rich fuels (and pre-combustion integration). ▪ *Gasifiers* have a large potential market (regardless of CCS) and should sustain improvement without CCS, hence less affected by demand uncertainty and barriers to novel concepts. However, **barriers to novel concepts** do exist for advances in fuel feeding for gasification and biomass gasification ▪ Early stage technologies face **barriers to novel concepts**	*Minimal failures, except for a few specific applications and integration issues*
Transport	3. **Key infrastructure dependency on uncertain public investment** – Large scale transport infrastructure requires long term planning, creating a ***need for government driven design optimisation and infrastructure planning*** (and ultimately infrastructure coordination/building)	*Critical failure*
Storage infrastructure and Mitigation & Remediation	*4.* **Long-term, global liabilities difficult to insure against** – individual companies do not have a strong commercial incentive to ensure long term reliability and robust risk mitigation methods for the desired long-term assurance; Moreover, limited insurance options (for very long run uncertainty) increase risks of CO_2 storage relative to returns. Together, these create a ***need for support across the innovation chain, from research through to demonstration*** 5. **Uncertain environmental impacts and regulatory regime** – health and safety regulation and public acceptance requirements associated with CO_2 leakage add to future uncertainty about necessary storage and M&R technologies, reinforcing the ***need for support for RD&D*** ▪ Market besides CCS is present in oil, gas and coal industry (EOR and ECBM), but not at the same scale or level of assurance as expected for CCS take-off	*Critical failure*
Storage characterisation and Measuring, Monitoring & Verification	▪ **Similarly affected by barriers (4) and (5) above** – individual companies do not have a strong commercial incentive to ensure the overall, long-term security of storage; limited insurance options (for very long run uncertainty) combined with uncertain regulation and public acceptance increase risks relative to returns. Together, these create a ***need for support across the innovation chain*** ▪ Market for accurate monitoring technologies is expected for the O&G industry, but not with as stringent requirements to ensure long term permanence	*Critical failure*
Full systems integration & fixed O&M	▪ **Policy dependent demand and uncertain support levels**, as well as **infrastructure dependency and uncertain public investment** inhibit market-based investment in optimising full systems integration and improving fixed operations and maintenance, ***creating a need for demo support***	Critical failure

*SCR, FGD, ESP = Selective Catalytic Reduction, Flue Gas Desulphurization and Electrostatic Precipitator

The UK can rely in part on other countries to drive innovation, but critical gaps likely to remain

For many CCS component technologies, the UK could likely rely on other countries to intervene in tackling these market failures, and in driving innovation with the focus, and at the pace, required to achieve much of the value to the UK.

In some areas, technologies are sufficiently generic and other countries are driving innovation at a pace likely to suffice for UK needs. These areas are:

- Pulverized coal boilers and turbines
- Gas turbine combined cycle (heat recovery steam generator/ steam turbine/ gas turbine)
- CO_2 compression

It is important to note that even in these areas, a lack of UK activity would probably have a negative effect on competitive advantage, and the ability to create new business opportunities. Moreover, there is always a risk that delays to progress in other countries (owing to a weakened commitment to tackling climate change, budgetary cut backs, or problems with public acceptance and local planning) could make such reliance costly to the UK. Nevertheless, the UK should avoid replicating work likely to be well advanced in other countries without strong justification.

In additional areas, the UK could rely in part on other countries, but there may be specific elements where the UK may want developments at a faster pace than is likely otherwise. And once again, a lack of UK activity would probably have a negative effect on competitive advantage, and the ability to create new business opportunities. These areas are:

- Capture components – The UK may want to drive the development of gas and biomass-related development more quickly than the rest of world
- Full systems integration and operations & maintenance – local demonstration required to build local skills deployable on a timely basis in the UK and adequate to UK circumstances

In a final set of areas, the UK has specific application needs which mean that achieving value to the UK is likely to require UK led efforts:

- Transport – Much of required innovation (especially around optimisation and health and safety requirements) needs to be aligned closely to local circumstances
- Storage, MMV and M&R – Offshore requirements different from most of the world, and much of required innovation needs to be aligned closely to local circumstances. *Could be benefits of working with North Sea countries*

Potential priorities to deliver the greatest benefit to the UK

The UK needs to focus its resources on the areas of innovation with the biggest relative benefit to the UK and where there are not existing or planned initiatives (both in the UK and abroad). The LCICG has identified a set of prioritised innovation areas.

Innovation areas with the biggest relative benefit from UK supported activity/investments

The LCICG has identified the sub-system/component areas of innovation with the highest potential benefit from UK public sector activity/investment (Chart 9)[11]. These are storage, MMV and M&R (especially offshore), followed by CO_2 capture (especially related to natural gas and biomass). There are also a few areas related to system integration with strong UK value opportunity, including transport system optimisation, overall plant operations, and potentially biomass gasification (and its integration). Finally, the LCICG has identified full-scale, source-to-sink CCS demonstration as a critical innovation need in order both to prove scalability of CCS (and its long-run availability to the system), as well as to drive cost-reduction opportunities related to full plant integration and to identify the most important component technology innovations going forward.

These areas have been prioritised according to the following criteria:

- value in meeting emissions targets at lowest cost
- value in business creation
- extent of market failure
- opportunity to rely on another country

[11] Without considering costs – these are considered in the final prioritisation.

Chart 9. Benefit of UK public sector activity/investment by sub-system area and technology component

Sub-area	Value in meeting targets, £bn, L – M – H			Value in business creation[1], £bn, L – M – H			Extent market failure	Opportunity to rely on someone else	Benefit of UK public sector activity (without considering cost)
Pollution control	0.0	**0.0**	0.1	0.1	**0.4**	0.7	Minimal	Yes, mature technology components	LOW
Capture components	1.7	**3.8**	7.1	0.3	**1.0**	1.9	Critical for some components	Yes, but (i) limited opportunity to rely on other countries to develop gas based concepts in timely fashion; (ii) UK has positions in oxyfuel technology that could accelerate international progress: (iii) early proof of concept could increase competitive advantage	MEDIUM-HIGH
Conversion & generation	1.3	**3.4**	6.7	1.0	**2.8**	5.6	Minimal (except gasification)	Yes, (mostly) mature technology component. RD&D required in pre-combustion concepts, but other countries leading development	LOW-MEDIUM
SOFC	0.3	**0.9**	1.8	0.0	**0.1**	0.2	Significant	Yes, but UK has strong position in fuel cells that could contribute to international progress and create competitive advantage	LOW
Overall plant efficiency	2.3	**4.2**	8.2	N/A			Significant	Yes, in terms of overall plant integration and key components (although UK will need to gain experience to optimise O&M)	MEDIUM-HIGH
Plant operations	N/A			0.3	**1.9**	3.6	Minimal	No for CCS chains in UK, need (local) staff and trained personnel. Services might be developed based on demos.	LOW-MEDIUM
Transport (CAPEX+OPEX)	0.0	**1.7**	4.8	0.3	**1.0**	1.7	Significant	Partially the NL and other leading countries, but UK will require some adaptation. Cannot rely on someone else to optimize design of UK infrastructure – UK has unique position for offshore transport	MEDIUM
Storage (CAPEX +OPEX)	1.9	**4.4**	8.3	0.3	**0.8**	1.5	Critical	Partially from Norway and the NL, but UK will require some adaptation – UK has unique position for offshore storage (incl. EOR)	HIGH
MMV and M&R	1.9	**4.0**	7.7	0.2	**0.5**	0.9	Critical	Partially from other industries/countries, but not clear if they will be ready in time. First proof of concept of MMV and risk remediation technologies will increase export value for UK technology	HIGH
Total (weighted average)	**9.5**	**22.3**	**44.7**	**2.5**	**8.3**	**15.9**	**Significant-Critical**		**HIGH compared to other technology areas**

[1] After displacement effects

Existing innovation support

Most UK activity is through project-based funding to project-specific partners, generally companies and universities/research institutes. **Five main funding bodies** for CCS RD&D in the UK drive much local activity: The Engineering and Physical Sciences Research Council, the Energy Technologies Institute, the Technology Strategy Board, the Department of Energy and Climate Change, and the Scottish Government.

The newly established UK CCS Research Centre seeks to coordinate research undertaken at universities and research organisations.

Various **knowledge sharing and collaboration networks** also exist, including the UK CCS Community Network, Advanced Power Generation Technology Forum, and the CCS Association

Finally, there are various **multi-lateral activities**, primarily around EU programmes

- Various FP6 and FP7 projects (e.g. CACHET, ENCAP, DECARBIT, CESAR/CLEO, INNOCUOUS, CO2Geonet, ECCO, RISCS, SITECHAR, CO2EUROPIPE) – participation led directly by UK companies and universities
- Near Zero Emissions Coal Project with China (NZEC) – expected to lead to plant construction and RD&D programme
- North Sea Basin Task Force and One North Sea Initiative – Joint cooperation mechanism with Norway
- Four Kingdoms Initiative – Collaboration mechanisms with Norway, the NL, and Saudi Arabia

Across these efforts, the UK is already supporting some of the areas highlighted above (Chart 10).

Chart 10. Summary of some existing UK public sector activity/investment

Sub-area	Existing activity	Key UK partners
Post-comb. capture	• **Ferrybridge CCPilot100+** – Amine solvent used to scrub the flue gas in a packed column. The solvent is boiled to release the CO_2 in a separate column and subsequently recycled back into the absorber (DECC-TSB, £6.3m public funding) • **Innovative Adsorbent Materials** and processes for integrated carbon capture and multi-pollutant control for fossil fuel power generation (EPSRC-E.ON Strategic Partnership)	• SSE, Doosan Babcock, Siemens, UK Coal, Vattenfall • Universities of Nottingham, Birmingham, Liverpool and UCL
Pre-comb. capture	• **The Next Generation of Activated Carbon Adsorbents** (£600k) – investigating materials and process development for the use of adsorption • **CCS on natural gas** (ESPRC, £5m, call launched 2011) • **Next Generation Capture I –** Demonstrate CO_2 removal by physical separation for gas-fired power plants (ETI, exp. £23.5m, starting 2012) • **Next Generation Capture II** – gas retrofit (ETI, £12.5m, call launched 2011)	• University of Nottingham • Tbd • Costain, U. of Edinburgh, Imperial College • Tbd
Oxy-fuel capture	• **Oxycoal Combustion UK** (EPSRC-E.ON, £1.7m) • Multi-scale evaluation of advanced technologies for capturing the CO_2 - chemical looping applied to solid fuels (£578k)	• 6 Universities: Leeds, Imperial, Cranfield, Kent, Nottingham and Cambridge • 4 Universities: Cambridge, Imperial, Nottingham and Surrey
Multiple capture technologies	• New technologies for CO_2 capture from power plant and biomass to capture CO_2 from the atmosphere (EPSRC-TSB, £4.7m) • **Carbon Abatement Technologies II** – Scale up of CAT proven at "lab scale" technologies for large single point emitters of CO_2, including power plants and energy intensive industries (TSB, £4.5m, call launched 2011)	• Edinburg U., Heriot-Watt U., DoosanBabcock, AirLiquide, Mott MacDonald, C-Questor, Scottish Enterprise and WWF • Tbd
Transport	• **COOLTRANS -** Optimised Transportation Networks (£300k, 2010 – 2013) • **MATTRAN** - Materials for Advanced CO_2 Transportation (EPSRC-E.ON, £1.59M , 2009 – 2013): Principally concerned with producing high quality data of relevant physical properties of CO_2 mixtures relevant to CCS	• Led by National Grid • Newcastle, UCL, Nottingham, Cranfield, Imperial, and a range of industry partners
Storage	• **ETI UKSAP** - UK CO_2 Storage Capacity • Caprock studies in low permeability labs • **CO_2 Leakage Prevention** Joint Industry Project • Assessment of theoretical potential of CO_2 storage in 'unmineable' coal seams in the UK • **CASSEM** - CO_2 Aquifer Storage Site Evaluation and Monitoring (EPSRC-TSB, £1.7m, ended 2010) • **CRIUS** - Fluid-rock interactions in reservoirs (EPSRC, £2.9m, 2010 – 2013)	• BGS, Senergy • Led by BGS • Herriot Watt University • Composite Energy, BG Group, Scottish Power, RBS, Imperial College & U. of Strathclyde • Heriot-Watt, Edinburgh, BGS, Manchester, with SSE, AMEC, Scottish Power, Marathon Oil, and Schlumberger • Cambridge, Leeds, BGS and Manchester
MMV and M&R	• Best practice for risk and environmental impact assessment, leakage, seepage, detection, rectifying and accounting • Static detection equipment and seismic monitoring	• BGS • …
Cross-cutting, other	• **UK CCS Research Centre** • **Public engagement project** (EPSRC, £0.1m, ended 2010) • **Sussex Energy Group (EPSRC, £2.8m, ended 2010) – included** work on CCS and policy (e.g. report "UK policy on carbon capture and storage: Squaring coal use with climate change?") • **ETI modelling tool-kit** capable of simulating the operation of all aspects of the CCS chain, from capture and transport to storage (ETI, £3m, launched 2011)	• Various • CCSI, Edinburgh • Sussex • Various

Potential priorities for public sector innovation support

In the sections above, we identified the areas of innovation with the highest potential benefit from UK public sector activity/investment, and looked at the breadth of existing UK support. These point to a number of priorities areas for potential public sector activity/investment by technology sub-area (see Chart 11). Many of these potential areas of UK activity build on existing UK activity. Moreover, in all cases, other countries are supporting work relevant to these high priority areas, and various opportunities for joint activity exist. The key priorities by type of support are:

1. Full integration across sub-areas

Full-scale, source-to-sink demonstration of integrated capture plant and transport/storage chain to prove concept at scale, and facilitate the availability of CCS to the energy system. Support would enable the demonstration of capture technology on a full-scale electricity plant, driving the development of improved construction techniques, improved operation and maintenance (in terms of lowest cost and highest reliability and flexibility), and more effective integration (especially across conversion and capture elements of the plant). It should also facilitate developments in the transportation and injection of CO_2, and allow the testing of various methods of the measuring, monitoring and verification process. In addition to the direct innovation benefits of the demonstration, it should also help identify the most critical sub-system and component innovation areas for future work, and could also serve as an overall platform for more specific RD&D of advanced sub-system/component technologies.

2. Sub-area innovation

2.i. Development and demonstration to improve promising sub-system/component technologies (post 'proof of concept'), and accelerate their move to commercial readiness. Support would span the 'proof of viability' and 'proof of scalability' stages, and generally involve a core capital investment around which multiple innovation projects can be built. Major areas for such projects in the UK would include:

- *Deep sub-sea storage and MMV:* Various initial projects related to identifying and assessing storage sites, best practice MMV protocols and developing key (early stage) storage and MMV technologies has taken place. In order to ensure the timely availability and security of CO_2 storage in the UK, the next stage is to move toward large-scale demonstration in deep sub-sea environments, and related component/model testing and development. This involves a significant scale up of activity to date, as well as opportunities to accelerate the development and commercialisation of various components. As such, it is best organised as a portfolio of projects around a limited number of major "programme" sites. Although a distinct UK project is warranted in order to ensure the UK has access to the required technologies and capabilities, our needs are similar to those of other North Sea countries, and it is worthwhile considering a joint programme as a way to make best use of limited resource.
- *Retrofit coal, gas and biomass capture components, and their integration:* The UK has a growing set of retrofit capture projects, with a first emphasis on coal (post-combustion) now complemented by projects with natural gas applications (pre-combustion). In both these areas, existing projects and investments could serve as platforms for continued proof of value/scale for promising technologies. In terms of UK-specific needs and the potential value of innovation, the biggest additional priority area would be issues specific to biomass firing or co-firing.
- *Multi-fuel gasification and capture components and their integration:* Various initial projects related to R&D of key components have taken place. The next stage is a larger scale development & demonstration programme connecting the full chain of activities from multi-fuel (coal, waste, biomass) gasification to multi-fuel output (liquid fuel, syngas, hydrogen) in combination with CO_2 capture, would enable various advances, especially in relation to the integration of CCS with biomass use.
- *Advanced conversion concepts with CCS:* Various initial projects related to R&D of key oxyfuel components has taken place. When considering the next stage of larger scale development & demonstration programmes, gas-fired oxyfuel concepts should also be considered (along with the capture technologies outlined above), with a focus on overcoming challenges in the boiler/turbine/GTCC area (e.g. for medium scale CHPs).

❖ With regard to the three capture and conversion related areas, the UK is only one of many countries supporting RD&D, and represents a relatively small market. As such, significant benefits may be possible through collaboration with countries at the forefront of technological development and/or those that represent significant future markets

2.ii. R&D of novel concepts with breakthrough potential. Support would be at or before the 'proof of concept', focussed on exceptional breakthroughs by international standards. Major areas for the UK would include:

- *Geological characterisation, performance simulation, and measuring, monitoring & verification*, especially in response to the feedback and key performance and cost challenges arising from demonstration work in deep sub-sea environments. Again, collaboration with other North Sea countries is worthwhile considering.
- *Mitigation & remediation*, with the goal of developing promising concepts to move into demonstration phase, perhaps as part of the demonstration work in deep sub-sea environments.
- *Capture concepts* that either address performance and cost challenges arising from demonstration work, or offer a major 'breakthrough' vis-à-vis existing concepts (and based on exceptional UK research). Again, significant benefits may be possible through collaboration with countries at the forefront of technological development

2.iii. Development and demonstration projects around commercial scale demonstration sites. The planned commercial-scale demonstration sites can serve as a platform for various innovation projects, especially related to process improvements. Major areas for the UK would include:

- *MMV at the capture point and along the transport network,* with a particular focus on ensuring compliance with likely health and safety requirements
- *Optimised operation of plants with CCS*, in terms of both O&M procedures and system integration improvements to increase efficiency of total plant

Supporting full integration through a full-scale demonstration requires a 5-10 year investment in the low billions of GBP across multiple demos.

Supporting all the sub-area innovations would require investment of hundreds of millions of Pounds in public sector funding, leveraging about 3 times that in private sector funding over the next 5-10 years. Moreover, specific elements of this programme could be funded at scale with millions to tens of millions of Pounds.

Whilst considerable, all these values are a fraction of the value that CCS innovation could bring to the UK economy.

Chart 11. CCS priorities for public sector activity/investment by technology sub-area (in addition to full scale demonstrations)

Technology area	Programme opportunities	Potential UK role	Scale of public funding to have material impact
Storage	• Development of tools for geological characterisation, performance simulation, and risk assessment (environmental impact assessment, etc.)	Lead funder (potentially in coordination with the North Sea consortium)	Millions of GBP
	• Development & demonstration of cost-reducing components and procedures for deep water injection and storage infrastructure (re-use and new build)		High tens of millions of GBP
MMV (storage)	• Development & demonstration of low-cost, high reliability, continuous monitoring options (e.g. remote or well bore sensing) for storage (especially deep-water)		Tens of millions of GBP
	• Development & demonstration of measurement tools for CO_2 flow and quality		Millions of GBP
M&R	• R&D of novel risk mitigation and remediation technologies for deep water storage, followed by early demonstration for promising concepts		Millions to tens of millions of GBP
Transport	• Design of optimised transport network, including onshore and offshore transport options, and cost/risk mitigation parameters, etc.	Lead funder	Low millions of GBP
	• Development & demonstration of low-cost, very high reliability, continuous monitoring options for MMV near to compression point, and along transport network	Lead or joint funder with international technology leaders	Low millions of GBP
Capture	• Development & demonstration of biomass related capture technologies (in combination with gasification demo) to accelerate promising technologies to commercial readiness	Lead funder	Tens of millions of GBP
	• Development & demonstration of retrofit capture technologies gas and/or biomass, and potentially for coal in areas where strong UK-based technology advantage exists	Joint funder with international leaders and/or lead markets	Millions to tens of millions of GBP
	• R&D of novel capture concepts with breakthrough cost reduction potential	Open calls (UK only)	Millions to tens of millions of GBP
Conversion and system integration	• Development & demonstration in the boiler/turbine/GTCC area of gas fired oxyfuel concepts (e.g. medium scale CHPs)	Lead or joint funder with international technology leaders and/or lead markets	Tens of millions of GBP
	• Development & demonstration of multifuel (coal, waste, biomass) gasification in combination with multifuel output (syngas, hydrogen, power and CO_2), in combination with integrated capture concepts		Tens of millions of GBP
	• Development & demonstration of services for optimised operation of power plants with capture (screening study potentially needed to identify clear priorities)		Millions of GBP

www.lowcarboninnovation.co.uk